A FUNDAMENTALS-BASED APPROACH TO MODELING OF TEXTURE DEVELOPMENT DURING SOME INDUSTRIALLY IMPORTANT PROCESSES

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ABSTRACT

Development of high-quality products and processes is easier with broader, integrated knowledge of the transformations that lead to final quality. A framework for the determination of Young's modulus (as an indicator of texture) for porous media multiphase models was developed and applied to a range of thermal food processes. This framework is easily implementable in commercial software and therefore has wide usage. The development of the fundamental framework for quality prediction of food processes and their implementation in commercial software requires local temperature and moisture from the fundamental physics-based process description.

Experiments were conducted to verify the change in the Young's modulus during these processes. The general framework developed makes it possible to predict the quality during different processes such as frying, baking, microwave heating and drying, starting from the same knowledge base. This can speed up product and process design, including development of novel products and processes.

BIOGRAPHICAL SKETCH

Shruti Thussu was born in Nainital, Uttarakhand in India. She went to elementary, middle and high school in this city and moved to Pantnagar for her undergraduate education in July of 2005. In 2009, she completed her Bachelors degree in Agricultural Engineering from G.B. Pant University of Agriculture and Technology, Pantnagar. During her stay at Pantnagar, she pursued some projects in mathematical modeling of food processes, which got her interested in the field of mathematical modeling with applications to food processing. In August of 2009, she joined the Department of Biological and Environmental Engineering at Cornell University, Ithaca, to pursue graduate studies in this field.

To my parents, Laskak Thussu and Rajni Thussu and brother, Sarthak.

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CHAPTER 1

TEXTURE PREDICTION DURING DEEP FRYING: A MECHANISTIC APPROACH

1.1 Abstract

A framework for fundamental physics-based prediction of texture was developed whereby changes in Young's modulus in potato strips during frying could be predicted by combining modulus changes with temperature and moisture with predictions of the latter from fundamental physics-based process model. Moisture and temperature dependence of Young's modulus was obtained from experiment. Process model for frying was based on multiphase porous media based transport equations. Effective value of Young's modulus for a potato strip was obtained from local values of modulus predicted by the model through homogenization. The predictions were validated using measured Young's modulus during frying. Such a model-based prediction providing insight into texture development during a frying process (both as function of time as well as spatially) within the potato strip will be difficult to achieve from direct experimentation. Precise effects of increased sample size and reduced oil temperature in slowing down the texture development are shown. Since the model is physics-based, the prediction framework can be extended to processes other than frying, allowing fundamental-based quality prediction in general.

Nomenclature

c	concentration, kg m^{-3}
c_p	specific heat capacity, J kg^{-1}K^{-1}
C	molar density, kmol m^{-3}
$D_{eff,g}$	effective gas diffusivity, m^{2}s^{-1}
D	diffusivity, m^2 s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_m	mass transfer coefficient of vapor, m s^{-1}
$\dot{I}$	volumetric evaporation rate, kg m^{-3} s^{-1}
k	thermal conductivity, W m^{-2} K^{-1}
k^p	permeability, m^2
K	non-equilibrium evaporation constant
m	overall mass fraction
$M = \phi S_w \rho_w / ((1-\phi)\rho_s)$	moisture content (d.b.)
M_a, M_v	molecular weight of air and vapor
n	total flux, kg m^{-2} s^{-1}
P, p	total pressure and partial pressure, respectively, Pa
R	universal gas constant, (J kmol^{-1} K^{-1})
S	saturation
t	time, s
T	temperature
u	velocity, m s^{-1}
V	volume, m^3
x	mole fraction

Greek Symbols

ρ	density, kg m^{-3}
λ	latent heat of vaporization, J kg^{-1}
ω_v, ω_a	mass fraction of vapor and air in relation to total gas
ϕ	porosity
μ	dynamic viscosity, Pa s

Subscripts

amb	ambient
a, *g*, *o*, *s*, *v*, *w*	air, gas, oil, solid, vapor, water
cap	capillary
eff	effective
eq	equilibrium
in	intrinsic
sat	saturation

1.2 Introduction and Objectives

Frying is a popular and industrially important food process. One of the primary determinants of quality of a fried food is its texture. Thus, prediction of texture development during frying can help us understand ways to manipulate the frying process (to achieve desired texture) and provide increasing ability for automation of the frying process.

During frying, the food is immersed into the oil at a high temperature that leads to vaporization of the water in the food. The food material first softens (Young's modulus decreases) due to thermal degradation from higher temperature and then, as it loses moisture, its modulus starts to increase. Both thermal degradation and texture development are functions of temperature and moisture (levels and/or history) that the food undergoes. Kinetics of textural changes have been studied by a number of researchers (Aguilar et al. 1997; Du Pont et al. 1992; Pedreschi, 2001). Change in Young's modulus of the crust during frying has been studied (Scanlon and Ross, 2004) experimentally but a physics-based model would provide clear relationship between the temperature and moisture changes and texture development.

Because the stimulus in texture perception is mainly mechanical, texture evaluation is done by mechanical measurements. Although many of these measurements cannot be related to a fundamental mechanical property, Young's modulus, that is a fundamental property (Figura and Teixeira, 2007), has been used as an accepted measure of texture (Vickers, et al. 1980; Rojo, et al., 2009). For example, Vickers (1980) has shown a linear dependence between crispness and Young's modulus. Thus, Young's modulus will be used as a measure for texture in our study. It is a measure of the stiffness of an isotropic elastic material and is defined as the ratio of the uniaxial stress over the uniaxial strain in the range of stress in which Hooke's Law holds.

In this study, our hypothesis was that the Young's modulus of a fried food (potato) is a function of temperature history and moisture level. Thus, if the change in Young's modulus with temperature and moisture is known, then predicting temperature and moisture will make it possible to predict Young's modulus during frying. We will use a physics-based model to predict temperature and moisture and combine these two parameters (or their histories as the case may be) to how they affect Young's modulus (obtained experimentally). This way we should be able to the predict the modulus development during frying, from product and process parameters. The predicted Young's modulus will be verified from direct experimental measurements of the same.

The manuscript is organized as follows. We first describe how the Young's modulus at a location (local values) is formulated in terms of its temperature and moisture dependence, and how an averaged Young's modulus is obtained from local values. A multiphase porous media transport model is described that provides the local temperature and moisture information and ultimately the Young's modulus, based on experimental relationships. Experiments to measure the effective Young's modulus at various times during frying are described. Results are described in terms of spatial and temporal changes in temperature, moisture and Young's modulus during frying and how they are affected by product parameter (sample size) and process parameter (oil temperature).

1.3 Problem Formulation

In this section, the mathematical modeling framework is developed for predicting Young's modulus during frying. Frying process involves simultaneous heat and mass transfer with changes in the materials that vary with space and time. A multiphase porous media based model for frying is developed that provides local temperature and moisture throughout the domain of the potato being fried. Using the local temperature and moisture content and the changes in Young's modulus with temperature and moisture obtained experimentally, local Young's modulus is computed. By performing a mechanical stress-strain analysis on the potato with the locally varying Young's modulus, an effective modulus of the potato is found.

1.3.1 Schematic

Potato in the shape of a French fry is considered here (Figure 1.1) with a size of $5 \times 5 \times 50$ mm and a square cross-sectional area of 5 mm $\times$ 5 mm. Considering it is long in the other dimension, a 2D heat and mass transfer analysis would be considered appropriate. Symmetry will further reduce the size of the domain.

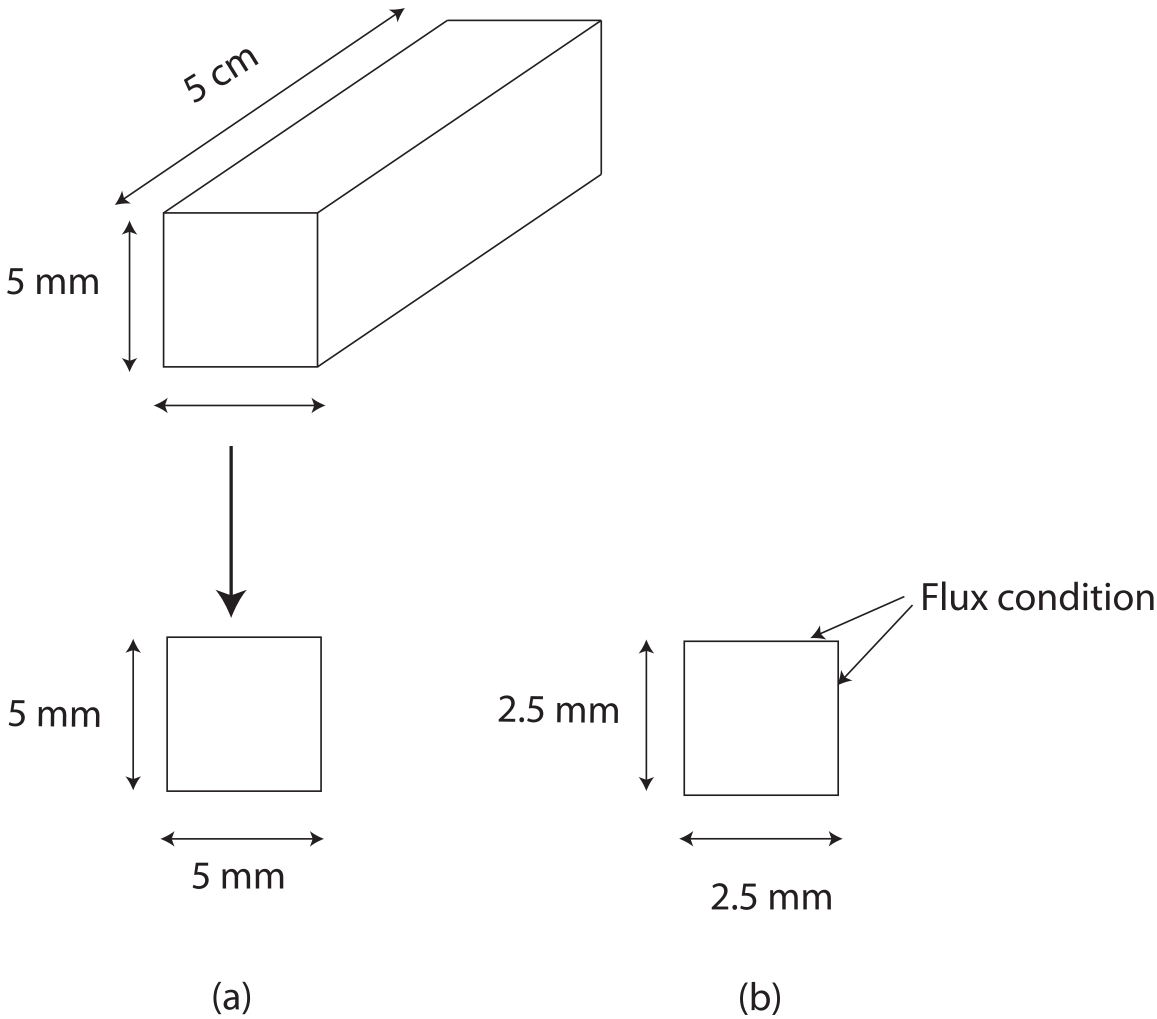

Figure 1.1: Schematic of the a) potato strip and the b) geometry used in computational model

1.3.2 Moisture and temperature dependence of Young's modulus: local values

The Young's modulus of potato was determined as a function of temperature and moisture content using mechanical measurements. The first-order kinetics for change in Young's modulus is written as (Lee, 2007):

$$\frac{\partial Y}{\partial t} = -k_f Y \tag{1.1}$$

where Y is Young's modulus. The temperature dependence of the rate constant is expressed by the Arrhenius equation

$$k_f = k_o \exp\left(\frac{E_a}{RT}\right) \tag{1.2}$$

where k_f is the rate constant at time t.

The model of fractional conversion provides improved accuracy and reliability in determining the texture degradation kinetics of vegetables (Rizvi and Tong, 1997). This fractional conversion model is used in the study. The fractional conversion model is derived from the first-order model. When using Young's modulus as a property, the fractional conversion model is written as:

$$f = \frac{Y_o - Y}{Y_o - Y_\infty} \tag{1.3}$$

where Y_o is initial modulus, Y is modulus at static time t, Y_∞ is modulus obtained after long times and f is the fractional conversion factor. Therefore, using Eqn. 1.3, the first order equation (Eqn. 1.1) is written as:

$$\frac{\partial(1-f)}{\partial t} = -k_f(1-f) \tag{1.4}$$

The temperature dependence is defined by the Arrhenius relationship.

In addition to temperature, there is moisture effect on Young's modulus. Change in Young's modulus with moisture content will be obtained experimentally.

Effects of both moisture content and temperature on Young's modulus were included to obtain their combined effect as

$$\frac{\partial Y}{\partial t} = \frac{\partial Y}{\partial M}\frac{\partial M}{\partial t} + \frac{\partial Y}{\partial T}\frac{\partial T}{\partial t} \tag{1.5}$$

where M and T are the local (at a location) values of moisture content and temperature, respectively.

Experimentally, the local values of Young's modulus with temperature and moisture content were ensured by using a very thin sample (about 1 mm thick) for measurements.

1.3.3 Moisture and temperature dependence of Young's modulus: Effective values through homogenization

Since the temperature and moisture histories will vary spatially, Young's modulus, Y as given by Eq. 1.5, will vary throughout the material. From these local values of Young's modulus, an effective value is needed that relates to sensory or typical instrumental value of texture. Process of obtaining effective or overall value from local values is called *homogenization*. Essentially, the effective value is obtained by performing mechanical analysis of the cross section with spatially varying modulus and, from the stress-strain information, computing the effective modulus. A static elastic iso-strain force-deformation problem with uniaxial loading is set up for the sample cross-section. An iso-strain level of 1.0

% is applied in one direction distributed over the cross-section to obtain effective modulus. Effective values of Young's modulus are computed using:

$$Y_{eff} = \frac{\int \sigma_{surf} dA}{0.01A} \tag{1.6}$$

This effective value of Young's modulus (Eq. 1.6), considered representative of texture, depends on local values of Young's modulus that in turn depends on moisture content and temperature that are obtained from process model as described below.

1.3.4 Frying model

The fundamentals-based model of multiphase heat and mass transfer in porous media from the work of Halder, et al. (2007) is used here. This model treats the food as a porous media and transport equations are developed for each of the phases of liquid water, vapor, air and oil. Several modes of transport are included. The process temperature and moisture predictions of this model have been validated against experimental data. Only essential details of the model are provided below and the reader is referred to Halder, et al. (2007) for further details.

Governing equations

Conservation equations are developed for all phases and components inside any phase, energy and Darcy flow in a porous media. Porosity, ϕ, is defined as the fraction of the total volume occupied by pores, given by

$$\phi = \frac{\sum_{i=w,g,o} \triangle V_i}{\triangle V} \tag{1.7}$$

where $\triangle V_i$ is the volume occupied by the i^{th} phase in an elemental volume $\triangle V$. Saturation of a phase is defined as the fraction of volume of the pore occupied by a particular phase

$$S_i = \frac{\triangle V_i}{\phi \triangle V} \tag{1.8}$$

where i stands for water, oil or gas.

Mass balance equation for a phase solves for saturation of the phase in an element. Saturations S_w and S_o are obtained from mass balance equations for liquid water and oil, respectively

$$\begin{aligned}
\frac{\partial}{\partial t}(\phi \rho_w S_w) + \nabla \cdot (u_w \rho_w) &= \nabla \cdot (D_{w,cap} \nabla(\phi \rho_w S_w)) - \dot{I} && (1.9) \\
\frac{\partial}{\partial t}(\phi \rho_o S_o) + \nabla \cdot (u_o \rho_o) &= \nabla \cdot (D_{o,cap} \nabla(\phi \rho_o S_o)) && (1.10) \\
S_w + S_g + S_o &= 1 && (1.11)
\end{aligned}$$

In Eqs. 1.9 and 1.10, the total flux of the liquid (water or oil) is due to the liquid pressure, $P - p_{cap}$, which is the difference between gas pressure and capillary pressure. This total flux term can be rewritten (e.g., see Datta, 2007), for example, for water as

$$\begin{aligned}
n_w &= -\rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \nabla(P - p_{cap}) && (1.12) \\
&= -\rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \frac{\partial p_{cap}}{\partial S_w} \nabla S_w && (1.13)
\end{aligned}$$

The first term in this equation is rewritten in terms of velocity, u_w, as explained later. The second term is rewritten in terms of capillary diffusivity, $D_{w,cap}$, given by

$$D_{w,cap} = -\frac{k^p_{in,w} k^p_{r,w}}{\phi \mu_w} \frac{\partial p_{cap}}{\partial S_w} \tag{1.14}$$

Similarly, capillary diffusivity of oil is defined by

$$D_{o,cap} = -\frac{k_{in,o}^{p} k_{r,o}^{p}}{\phi \mu_o} \frac{\partial p_{cap}}{\partial S_o} \tag{1.15}$$

The gas phase is a mixture of water-vapor and air. Spatial variations of concentration of water-vapor and air during frying are obtained from solving the respective mass conservation equations in terms of their mass fractions, ω_v and ω_a, with binary diffusion

$$\frac{\partial(\phi \rho_g S_g \omega_v)}{\partial t} + \nabla \cdot (u_g \rho_g \omega_v) = \nabla \cdot \left(\phi S_g \frac{C_g^2}{\rho_g} M_a M_v D_{eff,g} \nabla x_v \right) + \dot{I} \tag{1.16}$$

$$\omega_v + \omega_a = 1 \tag{1.17}$$

Darcy's equation for each phase in porous media replaces the standard momentum conservation (Navier-Stokes) equation. Since the effect of capillary pressure is included as a diffusion term, velocity of each phase is due to total pressure gradient as given by

$$u_i = -\frac{k_{r,i}^{p} k_{in,i}^{p}}{\mu_i} \nabla P \tag{1.18}$$

where i stands for water, oil or gas. The components of a phase (e.g., air and water vapor in gas phase) share the same velocity.

The total pressure, P, is calculated by solving the overall mass balance equation for the gas phase

$$\frac{\partial}{\partial t}(\phi S_g \rho_g) + \nabla \cdot (-\rho_g \frac{k_{r,g}^{p} k_{in,g}^{p}}{\mu_g} \nabla P) = \dot{I} \tag{1.19}$$

Since thermal equilibrium is assumed to exist between all phases (e.g., all phases have the same temperature), energy balance equation of the mixture (Eq. 1.20) is solved to calculate T

$$\frac{\partial}{\partial t}(\rho_{eff} c_{p,eff} T) + \nabla \cdot ((\rho c_p u)_{fluid} T) = \nabla \cdot (k_{eff} \nabla T) - \lambda \dot{I} \tag{1.20}$$

The properties of the mixture are averages of phase properties weighted by their mass or volume fractions. Equations 1.9, 1.10, 1.11, 1.16 and 1.20 are solved, together with the boundary conditions below, to obtain moisture and temperature, among other variables.

Boundary Conditions

As shown in Fig 1.1, to simulate a 2D situation, no flux conditions for mass species and energy are specified at boundaries other than $x = 0$ and $y = 0$.

$$\begin{aligned}
\text{B.C. for Eq. 1.19:} \quad & P_{surf} &=& \; P_{amb} & (1.21)\\
\text{B.C. for Eq. ??:} \quad & q_{surf} &=& \; h(T_{amb} - T_{surf}) - (\lambda + c_{p,w}T)n_{w,surf} & \\
& & & -c_{p,v} T n_{v,surf} - c_{p,o} T_{amb} n_{o,surf} & (1.22)\\
\text{B.C. for Eq. 1.9:} \quad & n_{w,surf} &=& \; h_m \phi S_w (\rho_{g,surf} \omega_{v,surf} - \rho_{v,amb}) & (1.23)\\
\text{B.C. for Eq. 1.10:} \quad & S_{o,surf} &=& \; S_{o1} & (1.24)\\
\text{B.C. for Eq. 1.16:} \quad & n_{v,surf} &=& \; h_m \phi S_g (\rho_{g,surf} \omega_{v,surf} - \rho_{v,amb}) & (1.25)
\end{aligned}$$

Input parameters and solutions process

The input parameters to the model are shown in Table 1.1. Properties of restructured potato, used by Halder, et al. (2007), were replaced by those of a regular potato and model was revalidated for these properties, as discussed in the Results section. The equations above are solved in a commercial software, COMSOL Multiphysics. As discussed earlier, further solution details are provided in Halder, et al. (2007).

1.4 Experimental Details

1.4.1 Drying experiments: Determination of moisture dependence of Young's modulus

Potato samples (Russet Idaho variety), clear of visible flaws, were used to study the change in mechanical properties. Thin slices of potato (size $8 \times 8 \times 1$ mm) were cut from the potato tuber. The average moisture content of a raw potato was found to be around 4.0 dry basis (db). By using a small sample, the drying and heating processes are assumed to occur uniformly throughout the sample. This allowed us to obtain local properties.

To determine the dependence of Young's modulus on moisture content, the sample was dried at 23°C and a constant relative humidity of 50% and the mass of the sample and its Young's modulus were recorded as a function of time. The Young's modulus values were determined using the DMA Analyzer (discussed later in Section 1.4.5). The mass of the sample was recorded using a balance with an accuracy of 10^{-5}g. The rate of drying (occurring over a period of 1-2 seconds due to change in velocity) during the sample transfer is neglected.

According to the ASAE Standard, the moisture content of a potato is evaluated by drying it for 24 hours at 72°C (Mazza, 1982). In our study, it was found

Table 1.1: Input parameters used in the simulations

Parameter	Value	Source
Density (kg/m^3)		
water (ρ_w)	998	
vapor (ρ_v)	Ideal gas	
air ρ_a	Ideal gas	
oil ρ_o	879	Tseng et al.(1996)
solid ρ_s	1528	Farkas et al. (1996b)
Specific heat capacity (J/kg K)		
water, c_{pw}	Eq. 45	Halder, et.al. (2007)
vapor, c_{pv}	Eq. 46	Halder, et.al. (2007)
air, c_{pa}	1006	Choi and Okos (1986)
oil, c_{po}	2223	Choi and Okos (1986)
solid, c_{ps}	1650	Choi and Okos (1986)
Thermal conductivity (W/m K)		
water, k_w	Eq. 47	Halder, et.al. (2007)
vapor, k_v	0.026	Choi and Okos (1986)
air, k_a	0.026	Choi and Okos (1986)
oil, (corn) k_o	0.17	Lewis (1987)
solid, k_s	0.21	Choi and Okos (1986)
Intrinsic permeability (m^2)		
water, $k^p_{in,w}$	5×10^{-14}	Ni and Datta (1999)
air and vapor, $k^p_{in,g}$	10×10^{-14}	Ni and Datta (1999)
oil, $k^p_{in,o}$	5×10^{-14}	Ni and Datta (1999)

Table 1.1 (Continued)

Parameter	Value	Source
Capillary diffusivity		
water, $D_{w,cap}$	Eq. 8	Halder, et.al. (2007)
air and vapor, $D_{o,cap}$	Eq. 9	Halder, et.al. (2007)
Viscosity (Pa s)		
water, μ_w	0.988×10^{-3}	
air and vapor, μ_g	1.8×10^{-5}	
oil, μ_o	$5.05 \times 10^{-6} \exp(\frac{2725}{T})$	Tseng et al.(1996)
Heat transfer coefficient (W/m^{2}K)		
Frying, h	Fig. 3a	Halder, et.al. (2007)
Mass transfer coefficient (m/s), h_m	Fig. 3b	Halder, et.al. (2007)
Latent heat of vaporisation (J/kg), λ	2.26×10^6	
Porosity, ϕ	0.88	Ni et al. (1999)
Vapor diffusivity in air (m^2/s), $D_{eff,g}$	2.6×10^{-6}	
Ambient pressure (Pa), P_{amb}	101325	

that the difference in the weight at the end of the room temperature drying process and after drying for 24 hours at 72°C was less than 0.001g. Thus, moisture content values reported are based on the weight at the end of the drying experiments. This is attributed to the small size (1mm thickness) of the sample.

All samples that had been once used for measurement of either moisture or Young's modulus were discarded. All such measurements were replicated three times to enhance the confidence and check variability. This provided the dependence of the Young's modulus on moisture content at constant temperature.

1.4.2 Heating in water: Determination of temperature dependence of Young's modulus (softening kinetics)

Dependence of Young's modulus on temperature and heating time (kinetics of softening) at constant moisture content was determined by heating the samples in water at two different temperatures of 85°C and 95°C, respectively. The sample size used was $8 \times 8 \times 1$ mm. The effect of any change in the moisture content during the entire heating process (samples lost moisture around 8% but the absolute moisture level was high) on Young's modulus was considered negligible in comparison to the temperature effect on the modulus. The temperature of a sample was measured by inserting a thermocouple from the edge of the potato slice during the entire process.

Samples were taken out of the water and their Young's modulus values at that time instant were measured in a DMA Analyzer for the two heating temperatures of 85°C and 95°C, respectively. A controlled furnace in the Analyzer maintained the environmental air temperature equal to the corresponding water temperature (85°C or 95°C) to minimize cooling of the sample. A sample was discarded after each measurement, i.e., a fresh sample was used for each duration of heating. For each time the Young's modulus was measured, three replications were done (using a different sample each time).

By curve fitting the Young's modulus versus time data (Fig. 1.2 shows this data for heating at 85°C) using Eq. 1.1, k_f was obtained for each of the two temperatures (85°C or 95°C). These k_f versus temperature values were fitted with Eq. 1.2 to obtain E_a. These values are shown in Tables 1.2 and 1.3.

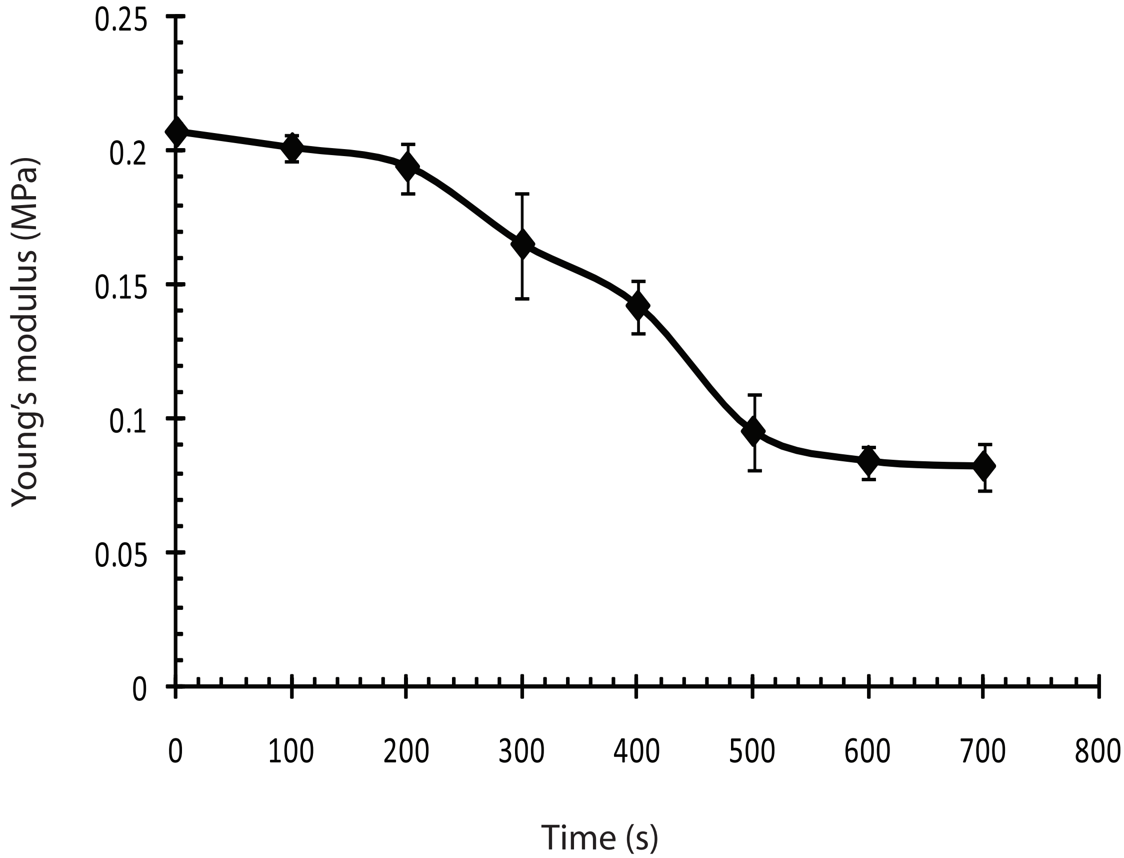

Figure 1.2: Change in Young's modulus with time while heating in water at 85°C

1.4.3 Frying experiments

Moisture content and Young's modulus were measured at different time steps during frying. Same potatoes, as mentioned earlier, and pure corn oil were used to carry out the frying experiments. The potatoes were washed and peeled before cutting. The potato samples of size $5 \times 5 \times 50$ mm were used for the frying experiments. Two slices per sampling time were fried in 300 ml of hot oil in a fume hood at each of the four temperatures (140°C, 150°C, 160°C, and 170°C). One of the samples was used for measurement of moisture content and the other for measuring Young's modulus. The temperature of the sample was measured by inserting a thermocouple from the edge of the potato during the entire process. The moisture content was measured by putting the fried sample in the oven for 24 hours at 72°C, following ASAE standards. Both of these samples were discarded after the measurement and a fresh sample was used for a different duration of frying. Three sets of such experiments were performed for each value of oil temperature and frying duration.

For each selected sampling time, the slices were drained by patting on absorbent paper after frying and put in DMA within a few seconds to measure their mechanical properties. The chamber in DMA where the sample was placed was temperature controlled and frying temperature was maintained inside the chamber.

1.4.4 Mechanical properties

Young's modulus was measured using compression tests in a Q800-0666-DMA Q800 Analyzer during the processes of constant temperature drying, heating in water and frying. The strain rate of the probe was 1.0%, which is within the elastic range in the case of potato (Skinner, 1983). The Young's modulus was determined using the compression test at each stage of drying (at different levels of moisture), water heating and frying. This was done by applying a constant strain on the material for 30 seconds and measuring the corresponding stress generated, from which Young's modulus was obtained.

1.5 Results and Discussion

Kinetics of changes in Young's modulus with moisture and temperature, obtained experimentally, is presented first. Temperature, moisture and Young's modulus changes during frying, as predicted by the model, are presented next, along with experimental data, whenever appropriate. Effect of sample size and oil temperature on modulus development during frying is presented as sensitivity analysis to the model.

1.5.1 Kinetics of changes in Young's modulus with moisture and temperature

As shown in Fig. 1.3, Young's modulus increases with decreasing moisture content. The solid line shows the data used as input parameters in mechanical analysis in COMSOL Multiphysics. The decrease in moisture content results in the sample toughening. This toughening of the sample leads to an increase in the Young's modulus as can be seen in Fig. 1.3. Temperature effect on Young's modulus, obtained from heating experiments described earlier, are shown in

Table 1.2: Determination of kinetic parameters at 85°C

k_f (/min.)	E_a (kJ/mol)
0.372	53.95
0.5595	92.83
0.6579	70.93

Table 1.3: Determination of kinetic parameters at 95°C

k_f (/min.)	E_a (kJ/mol)
0.1165	65.95
0.1494	40.34
0.4712	86.78

Tables 1.2 and 1.3, respectively.

1.5.2 Changes in moisture and temperature during frying

Fig. 1.4 shows the change in moisture content during frying of potato strips, obtained from the model as well as from experiment. The comparison between models predictions and experimental data is quite reasonable, especially considering there are no fitting parameters in the model. Fig. 1.5 shows how the values of moisture content vary spatially throughout the domain of the food material.

Similarly, temperature of the crust with time was compared with measured temperature at the crust, as shown in Fig. 1.6. Representative spatial variation of temperature within the potato cross section is shown in Fig. 1.7.

1.5.3 Changes in Young's modulus during frying

Effective values of Young's modulus, obtained as described under Problem Formulation, are presented in Fig. 1.8 during frying of a 5×5 mm sample. These predictions at four different oil temperatures are also compared with the corresponding experimentally obtained values, showing good comparisons.

It can be added here that since the size of the sample (5×5 mm) being somewhat small, the initial softening due to rise in temperature occurs in the center only for small durations. This is followed by crust development that is the dominant effect of moisture loss. However, as the drop in Young's modulus (due to rising temperature effect) is small compared to its increase due to moisture loss, the effective values of the Young's modulus are never seen to drop.

Another interesting observation is the near linear relation between the values of effective Young's modulus and volumetric average Young's modulus defined as

$$Y_{vol} = \frac{\int Y dv}{V} \tag{1.26}$$

as shown in Fig. 1.9. As it is easier to compute the values of volumetric average Young's modulus (by averaging the local information obtained on Young's modulus), in some situations volumetric average modulus may suffice.

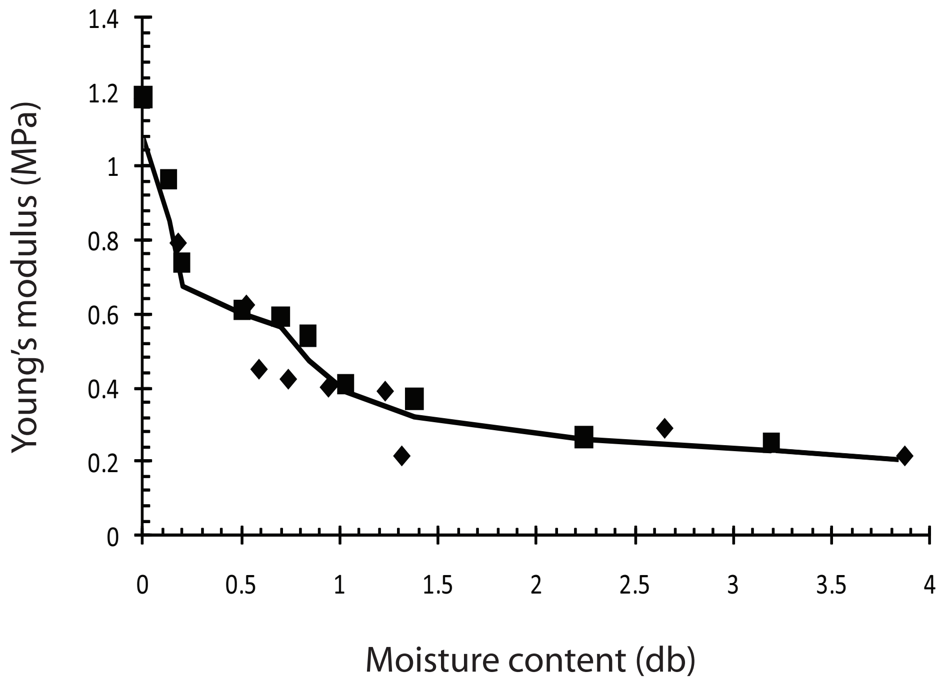

Figure 1.3: Change in Young's modulus with changing moisture content

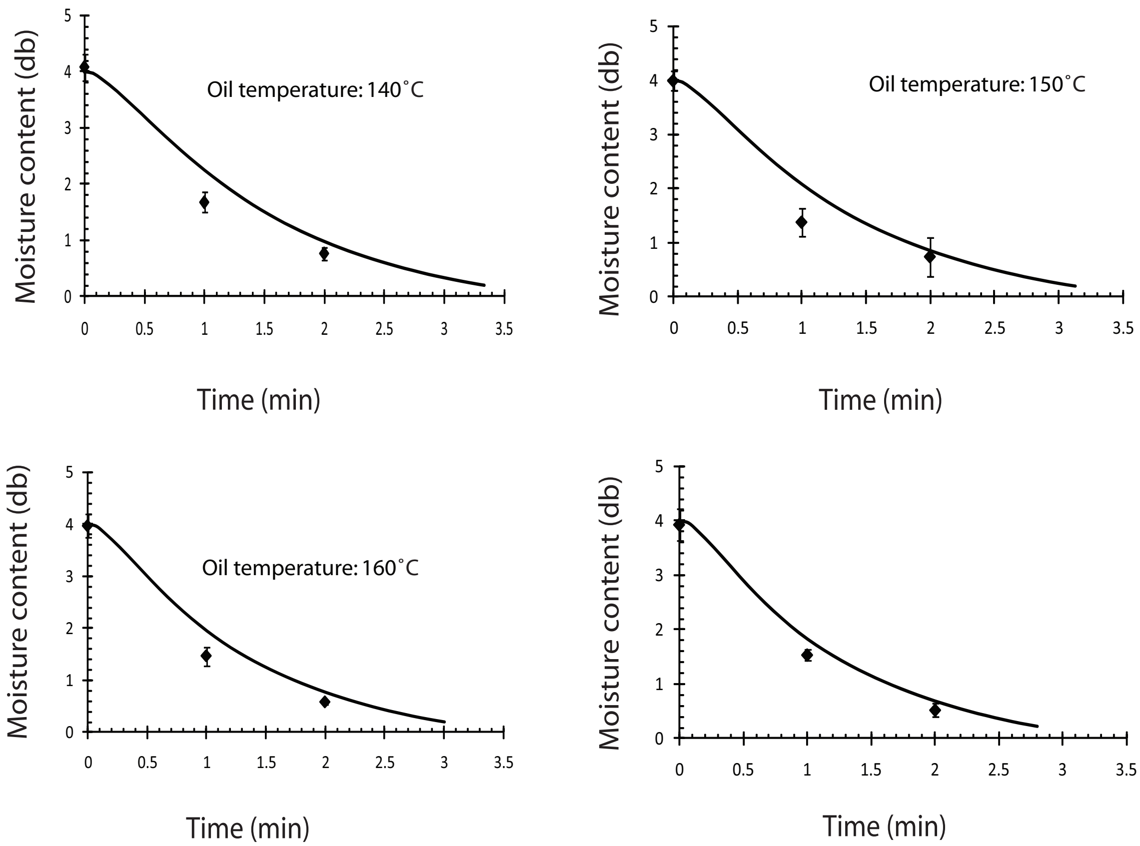

Figure 1.4: Change in moisture content during frying at all temperatures

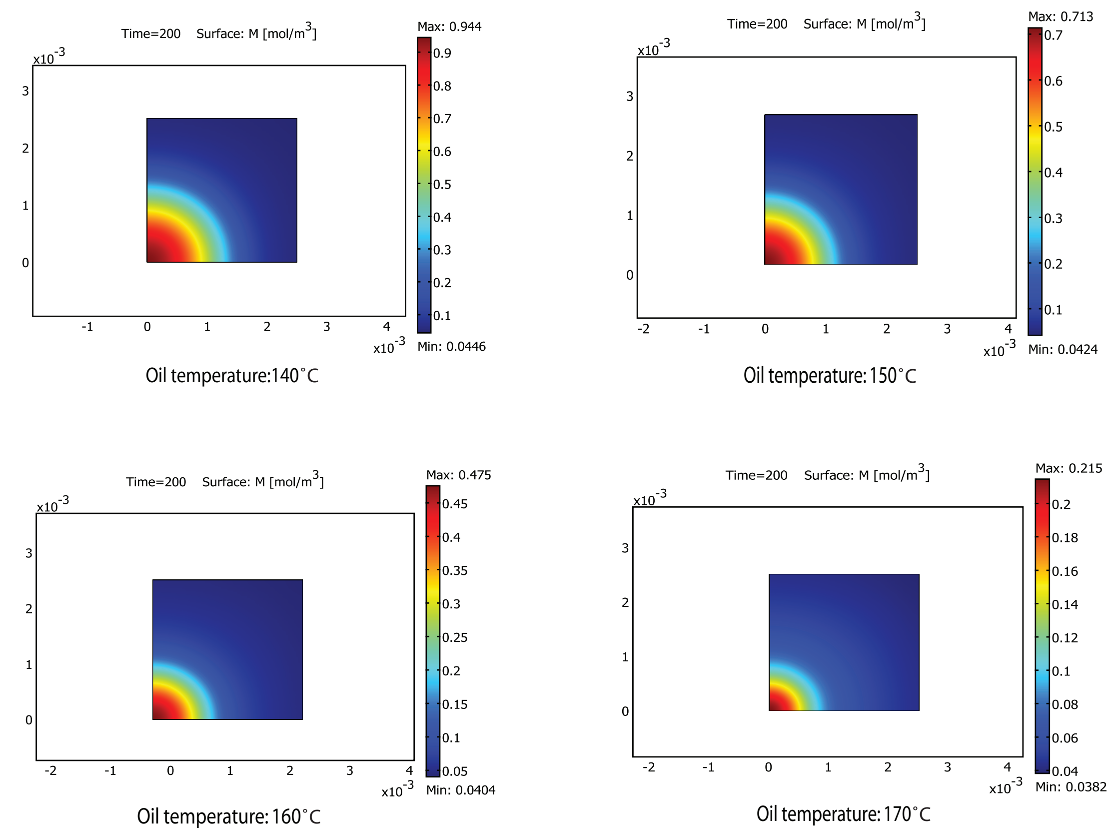

Figure 1.5: Spatial variation of moisture content after 200 s

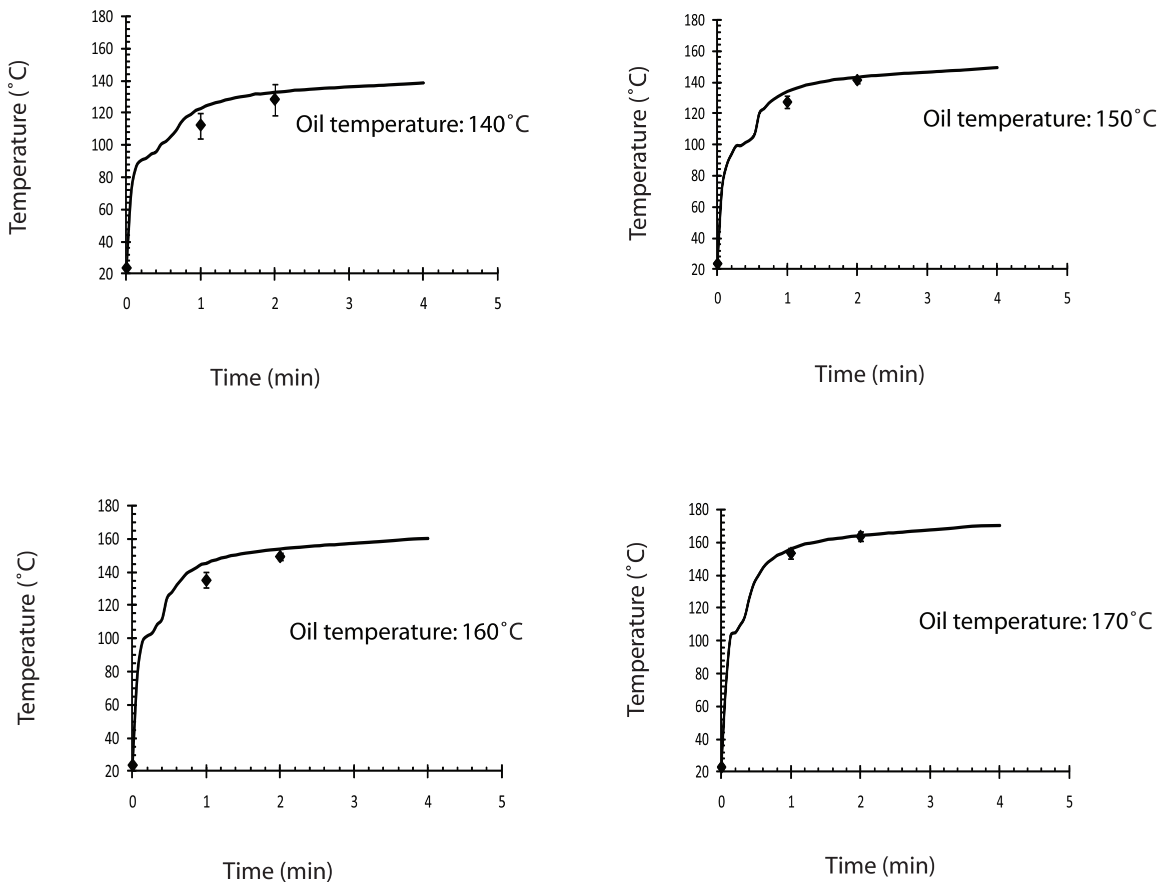

Figure 1.6: Change in temperature during frying at four different temperatures

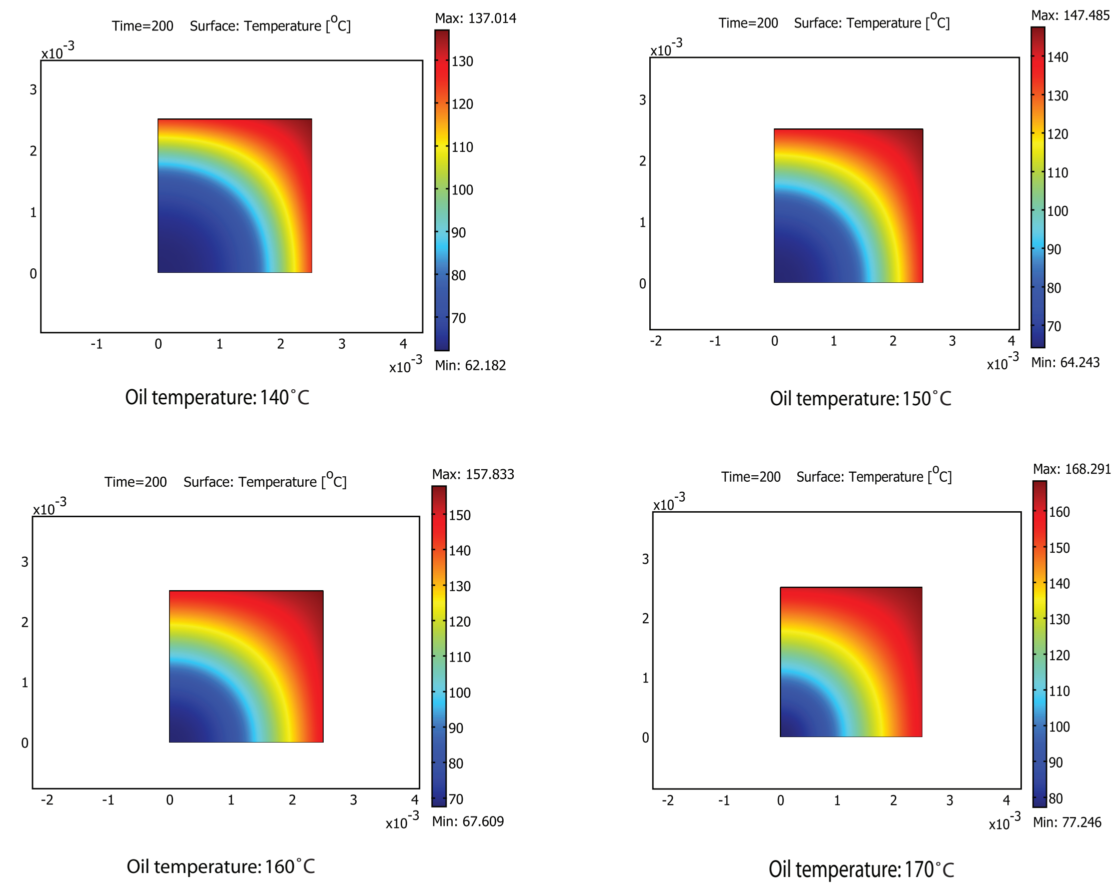

Figure 1.7: Spatial variation of temperature during frying after 200 s

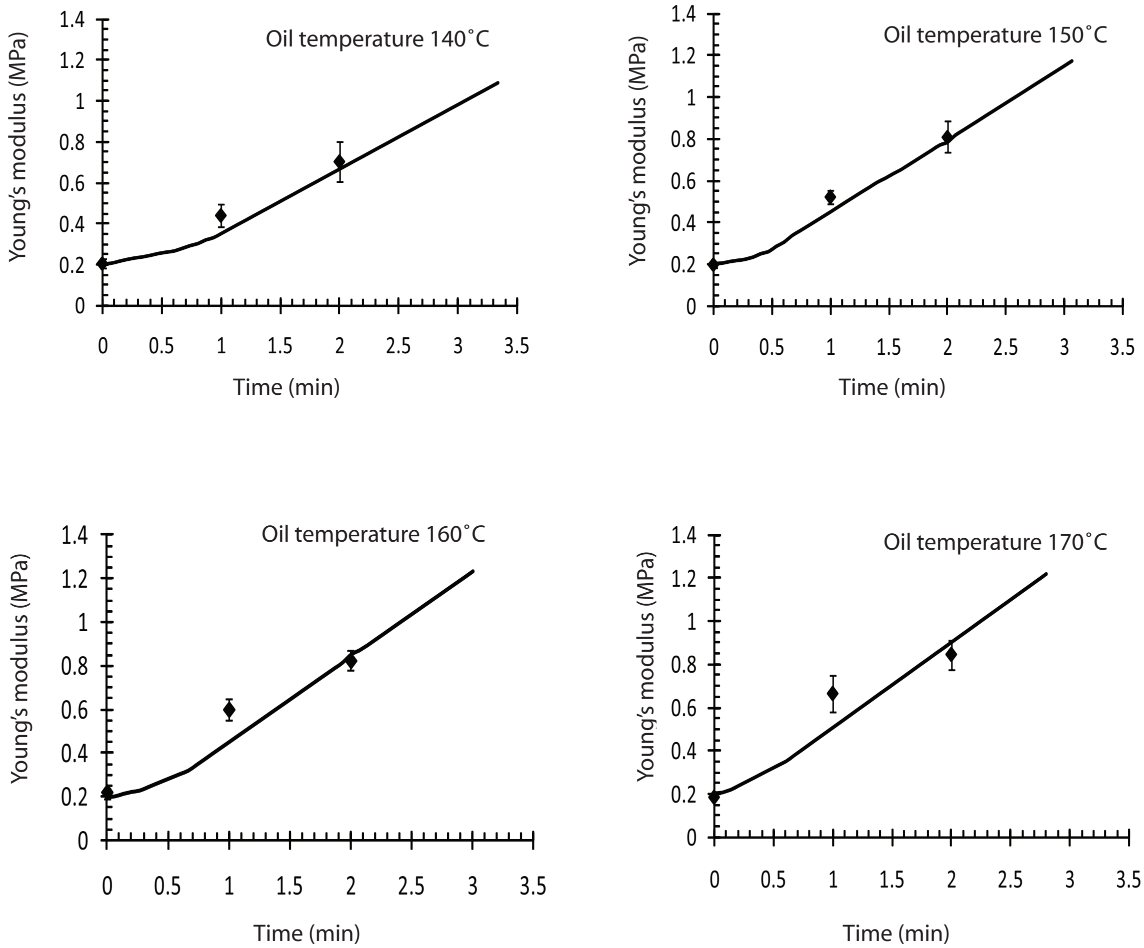

Figure 1.8: Change in effective Young's modulus during frying at various temperatures. Points showing experimental data

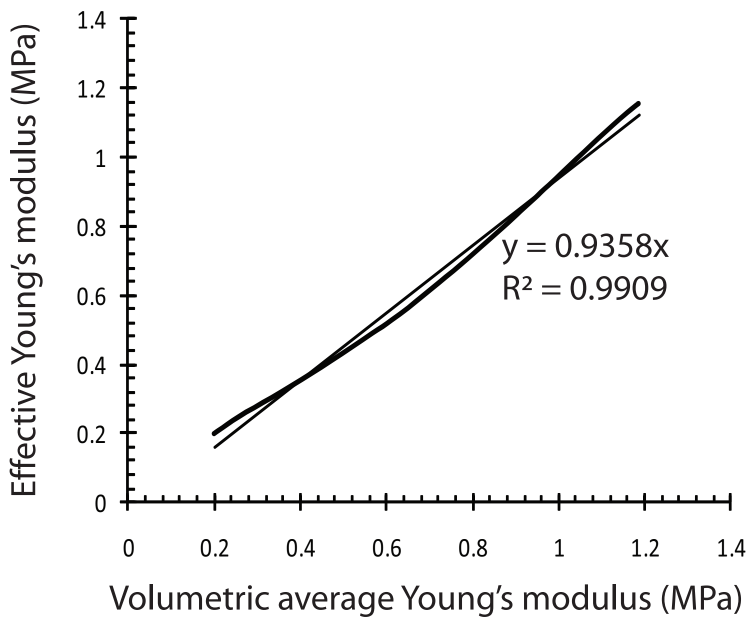

Figure 1.9: Comparison of effective and volumetric average Young's modulus at 150°C

1.5.4 Effect of sample size on texture development

Moisture loss during frying is slower for larger sizes, as expected (shown in Fig. 1.10a). This results in continued softening (decreased Young's modulus or staying low) of the sample before starting to increase due to moisture loss, as shown in Fig. 1.10b. Thus, with increase in sample size, texture development is slower (Young's modulus is lower). Fig. 1.11 shows the differences in time taken for samples of different sizes to reach the same (desired) level of Young's modulus. It is interesting to note that the time taken to reach the desired level of texture is linearly proportional to the sample size. Such relationships provide insight into the texture development process and allows easy implementation of the findings in a process control system.

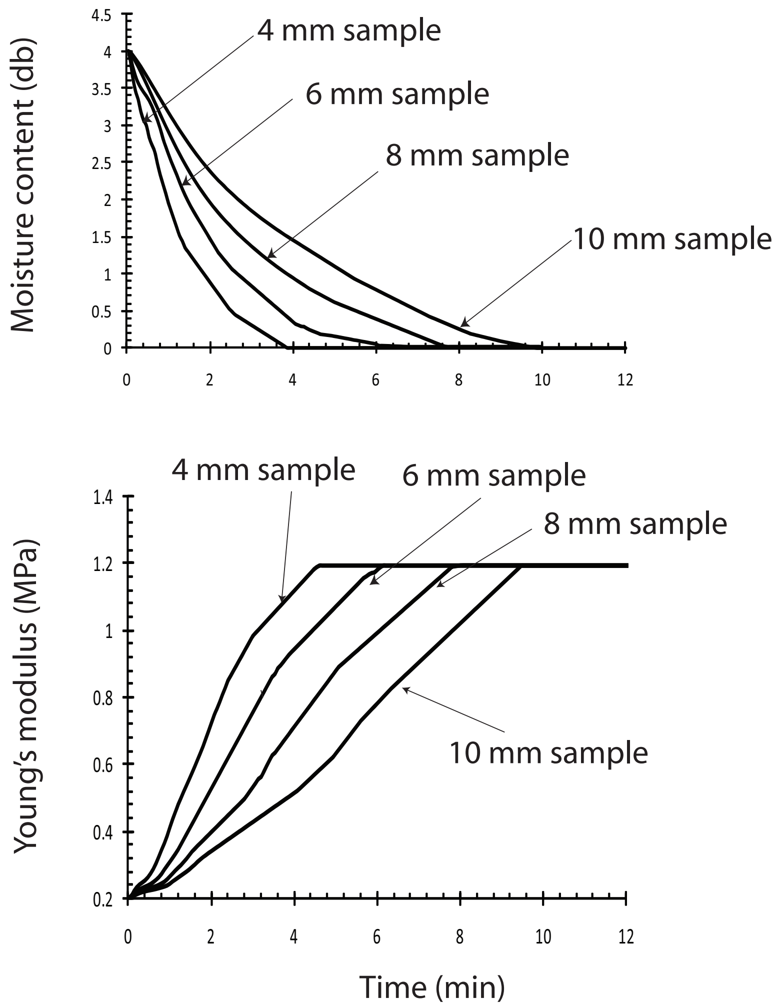

Figure 1.10: Size effect on variation of a) moisture, and b) Young's modulus with time during frying. As size increases, there is increased lag time before modulus starts to increase. Also, modulus increase is slower for larger size since moisture loss is slower

1.5.5 Effect of oil temperature on texture development

Fig. 1.12b shows the changes in Young's modulus during frying of a 5 mm sample at different oil temperatures. As expected, with increasing oil temperature, moisture loss is quicker (Fig. 1.12a). The time taken by the sample to reach the desired value of Young's modulus (signifying texture) decreases with increase in oil temperature as shown in Fig. 1.13. Analogous to the effect of sample size on frying time (to reach the same desired value of Young's modulus), an increase in the oil temperature also results in a decrease in frying time, although the decrease is not really linear.

Crispness of food is known to increase with higher oil temperature (Loon, 2005). This goes well with our observation in Fig. 1.13 that for a particular duration of frying, the Young's modulus of the sample is higher when fried at a higher temperature.

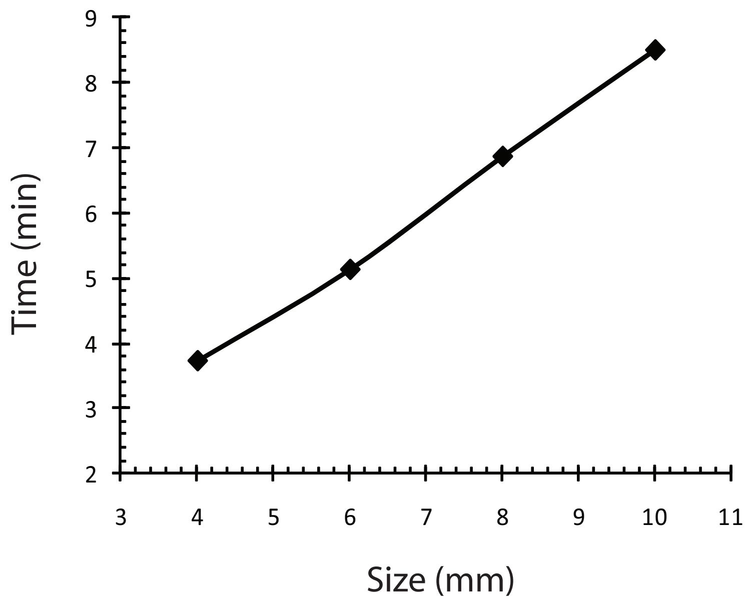

Figure 1.11: Time required by various sample sizes to reach the same desired texture level (Young's modulus value of 1.08MPa), as obtained from Fig. 1.10b

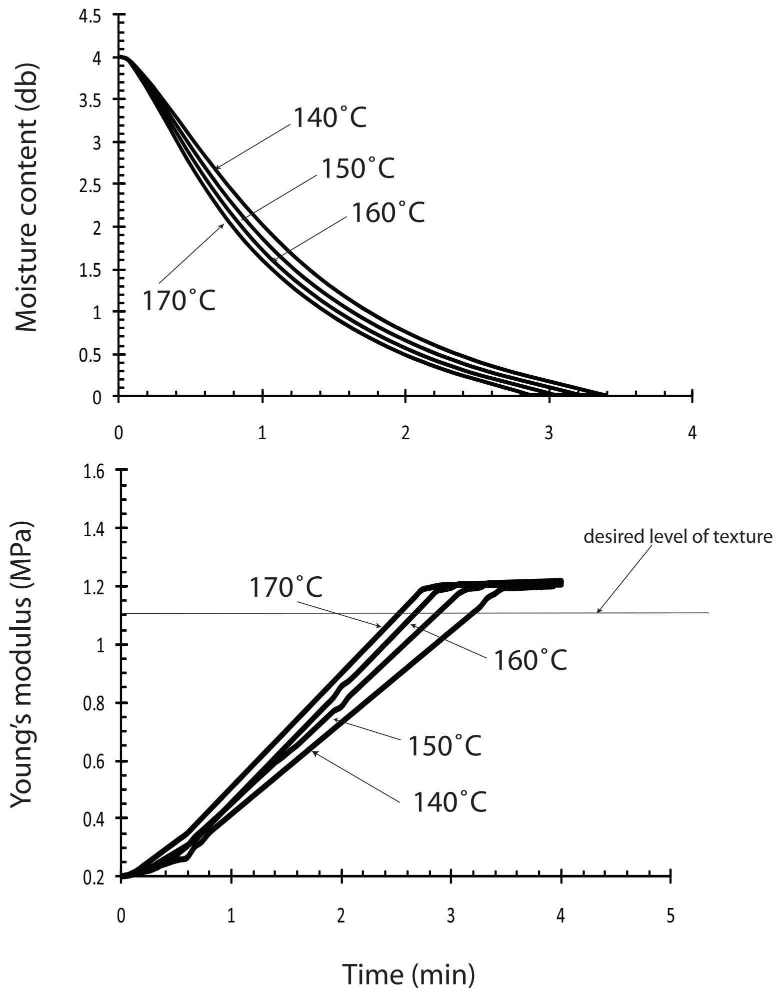

Figure 1.12: Effect of oil temperature on variation of a) moisture and b) Young's modulus with time during frying. As oil temperature increases, there is less of a lag time before modulus starts to increase. Also, modulus increase is faster for higher oil temperature since moisture loss is faster

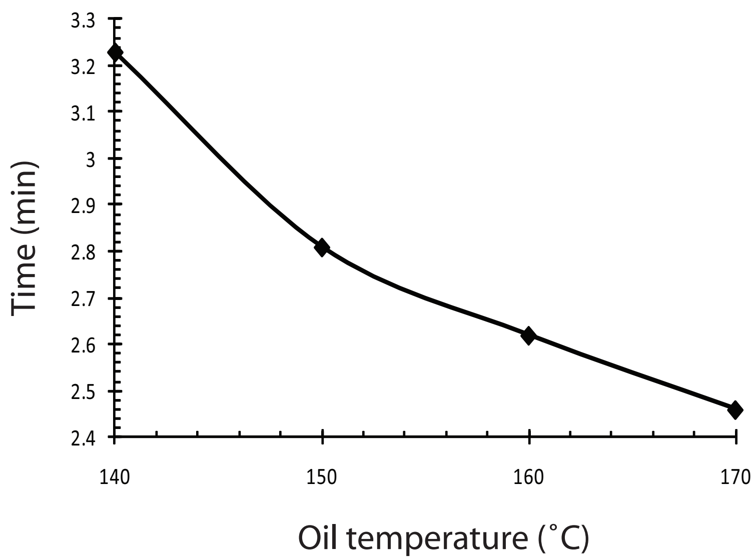

Figure 1.13: Time required at various oil temperatures to reach the same desired texture level (Young's modulus value of 1.08), as obtained from Fig. 1.12b

1.6 Conclusions

Using moisture and temperature variation of Young's modulus measured from experiment, it was possible to predict texture (Young's modulus) development during frying of potato strips from physics-based or mechanistic model, without any fitting parameters. The predictions were validated using measured Young's modulus during frying. Such a model-based prediction provided insight into spatial and temporal variation of texture during a frying process and how it is affected by sample size and oil temperature. Since the model is physics-based, the prediction framework can be extended to processes other than frying, allowing fundamental-based quality prediction in related processes such as drying and baking.

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CHAPTER 2

A FRAMEWORK FOR SIMULATION OF TEXTURE DEVELOPMENT DURING DRYING AND RELATED PROCESSES

2.1 Abstract

Using Young's modulus as a measure for texture, a framework for predicting the effective modulus of a solid food material is extended to four moisture removal processes. The effective modulus is predicted using mechanical analysis from local modulus values that depend on transient moisture and temperature. For the process of frying, the development of modulus could be predicted from the same dependence of moisture and temperature as was done for frying in an earlier study. These predictions compared well with experimentally measured modulus. The prediction framework is then extended to the processes of baking and microwave heating. The moisture and temperature information needed for prediction of modulus is in turn obtained from multiphase porous media-based models of the processes, thus making physics-based texture prediction possible from process and product parameters. Texture development during four moisture removal processes are compared with each other and the effect of oven temperature and sample size is discussed.

Nomenclature

c	concentration, kg m^{-3}
c_p	specific heat capacity, J kg^{-1}K^{-1}
C	molar density, kmol m^{-3}
$D_{eff,g}$	effective gas diffusivity, m^{2}s^{-1}
D	diffusivity, m^2 s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
h_m	mass transfer coefficient of vapor, m s^{-1}
$\dot{I}$	volumetric evaporation rate, kg m^{-3} s^{-1}
k	thermal conductivity, W m^{-2} K^{-1}
k^p	permeability, m^2
K	non-equilibrium evaporation constant
m	overall mass fraction
$M = \phi S_w \rho_w/((1-\phi)\rho_s)$	moisture content (d.b.)
M_a, M_v	molecular weight of air and vapor
n	total flux, kg m^{-2} s^{-1}
P, p	total pressure and partial pressure, respectively, Pa
R	universal gas constant, (J kmol^{-1} K^{-1})
S	saturation
t	time, s
T	temperature
u	velocity, m s^{-1}
V	volume, m^3
x	mole fraction

Greek Symbols

ρ	density, kg m^{-3}
λ	latent heat of vaporization, J kg^{-1}
ω_v, ω_a	mass fraction of vapor and air in relation to total gas
ϕ	porosity
μ	dynamic viscosity, Pa s

Subscripts

amb	ambient
a, *g*, *s*, *v*, *w*	air, gas, solid, vapor, water
cap	capillary
eff	effective
eq	equilibrium
in	intrinsic
r	relative, residual
sat	saturation

2.2 Introduction and Objectives

Although texture development in foods is a widely studied subject (e.g., Tijskens and Luyten, 2004), it is typically studied empirically. Completely empirical models of texture, which are often used to study food texture, can be useful for specific situations and for applications such as automated process control, but they do not provide much understanding of the fundamental mechanisms involved. Investigations using such models are frequently limited to a particular food under study, so that the results cannot be generalized. A framework for a quantitative, first-principle-based understanding of food quality should make science-based decision-making and problem solving for food product and process developers easier. Such a framework should also prove to be useful in an education environment. For example, texture development in processes that can provide alternatives to deep frying (and thus be more desirable from a health standpoint) can be better understood so that such processes can be developed in a more predictable manner.

Food process models that have become increasingly sophisticated in recent years (e.g., Farid, 2010; Sablani et al., 2007) typically stop at predicting basic parameters such as temperature and moisture and are incapable of predicting a mechanical quality parameter such as texture. However, as described in the following paragraph, such models can offer a starting point for texture prediction. Once the kinetics of texture developments are known, it may be possible to combine the kinetics of texture development with process models to predict texture development from a more fundamental approach than has been reported in the literature.

Process models themselves are not the focus of this study. We have developed a porous-media-based framework (Datta, 2007) that can effectively model a large class of food processes such as baking, drying, frying, and microwave heating. We will use or develop (depending on what already exists in the literature) individual process models based on this porous-media framework of process models. In these processes, often significant internal evaporation and resulting pressure generation lead to pressure-driven flow. Both the spatially varying rates of internal evaporation and the pressure-driven flow make the physics quite complex, but are critical components providing a realistic process description that is essential for quality prediction. The flow of three phasesair, water vapor, and liquid waterin a porous medium is considered here. Flow of other phases such as oil is also included in an analogous manner (Thussu and Datta, 2010). Local thermal (not moisture) equilibrium is assumed, and all gases are assumed to be ideal. Mass conservation of the three phases are set up. The mass fluxes consist of not just diffusion (for gases) or capillary diffusion (for liquid), but also of pressure-driven flow of all vapor, air, and water. Although many drying models exist in the literature, the general applicability of this porous-media-based model over many processes makes it ideal for developing a generalized framework for texture development that can transcend simple drying and be applicable to many other processes.

Changes in mechanical properties during a drying process have been studied for various materials (e.g., Borrega et al., 2009; Krokida et al., 1998). In the case of potato, two mechanisms of degradation of structural components and formation of irreversible hydrogen bonds contribute to changes in mechanical properties (Lee, et al., 2007). Gelatinization of potato starch at 61.1°C (Shiotsubo, 1984) can cause significant changes in mechanical properties (Lee, et al., 2007). However, dependence of mechanical properties on moisture and temperature has not been appropriately quantified in a manner useful for analysis using solid mechanics.

Although texture is hard to quantify in terms of engineering measurements, Young's modulus has been shown to be a relevant parameter to characterize systems such as cellular materials that are soft solids (Walstra, 2003) under conditions that prevail in the mouth during chewing. Textural attributes such as hardness and softness can be related to Young's modulus (Figura and Teixeira, 2007). The mechanical properties are due to the presence of structural elements in the food: cell walls, colloidal particles, biopolymer networks. Processing affects these structural elements because of chemical and physical reactions. Like any property, Young's modulus may vary with position in the material since the temperature or moisture histories may also vary within the material. The overall property of the material will be a composite (in the mechanical sense) of the locally varying properties. If the kinetics of the property changes are known, the quality kinetics can be combined with the process model to obtain local quality, from which the overall quality can be obtained following ideas from solid mechanics (Nemat-Nasser and Hori, 1999). This approach has been successfully applied to a simple process of cooking of potatoes in water where the property is a only function of temperature history only (Lee et al., 2007). Developing such a fundamentals-based prediction of texture as a function of both moisture and temperature that applies to more than one process is the objective of this study.

The manuscript is organized as follows. The process model formulation for drying, baking, and microwave heating of potato strips is developed. Experiments to measure Young's modulus as a function of the drying time of the potato strips are described. Results for temperature, moisture, and Young's modulus development with time during drying are shown from computation and compared with experimental results, for various drying temperatures. Predictions of texture are extended to the processes of baking, frying and microwave heating and the four processes are compared side by side.

2.3 Mathematical Model

In this section, a mathematical framework is developed for predicting Young's modulus of a food material (potato), during the processes of drying, baking and microwave heating. The framework involves multiphase porous media based process-model that provides temperature and moisture fields throughout the domain of the food sample. Relationship between Young's modulus of the food material and its moisture and temperature content is experimentally determined. Now, once the temperature and moisture fields are predicted from the process model, the local Young's modulus values in the food sample can be estimated. A stress-strain analysis is then performed, in which The food material is then subjected to fixed uniaxial compression strain (small) to obtain the resulting. The ratio between the predicted stress and the applied strain is then defined as the effective Young's modulus of the material. Since the temperature and moisture fields vary with the process duration, the effective Young's modulus also varies.

Mathematically, the net rate of change of Young's modulus is the sum of changes due to temperature and moisture, expressed as:

$$\frac{dE}{dt} = \frac{\partial E}{\partial M}\frac{dM}{dt} + \frac{\partial E}{\partial T}\frac{dT}{dt} \tag{2.1}$$

where M and T are the local (at a location) values of moisture content and temperature, respectively. Experimental determination of temperature and moisture dependence of Young's modulus ($\frac{\partial E}{\partial T}$ and $\frac{\partial E}{\partial M}$, respectively) is discussed elsewhere (Thussu and Datta, 2010). Rates of change of temperature and moisture ($\frac{dT}{dt}$ and $\frac{dM}{dt}$, respectively) are obtained from the process model.

2.3.1 Schematic

Prediction of effective Young's modulus during drying of a potato strip (Figure 2.1), with dimensions of 5 mm $\times$ 5 mm $\times$ 50 mm is considered for model validation. As the strip is long in one direction, a 2D heat and mass transfer analysis on the square cross-section (5 mm $\times$ 5 mm) is considered to determine temperature and moisture fields. Symmetry further reduces the domain size.

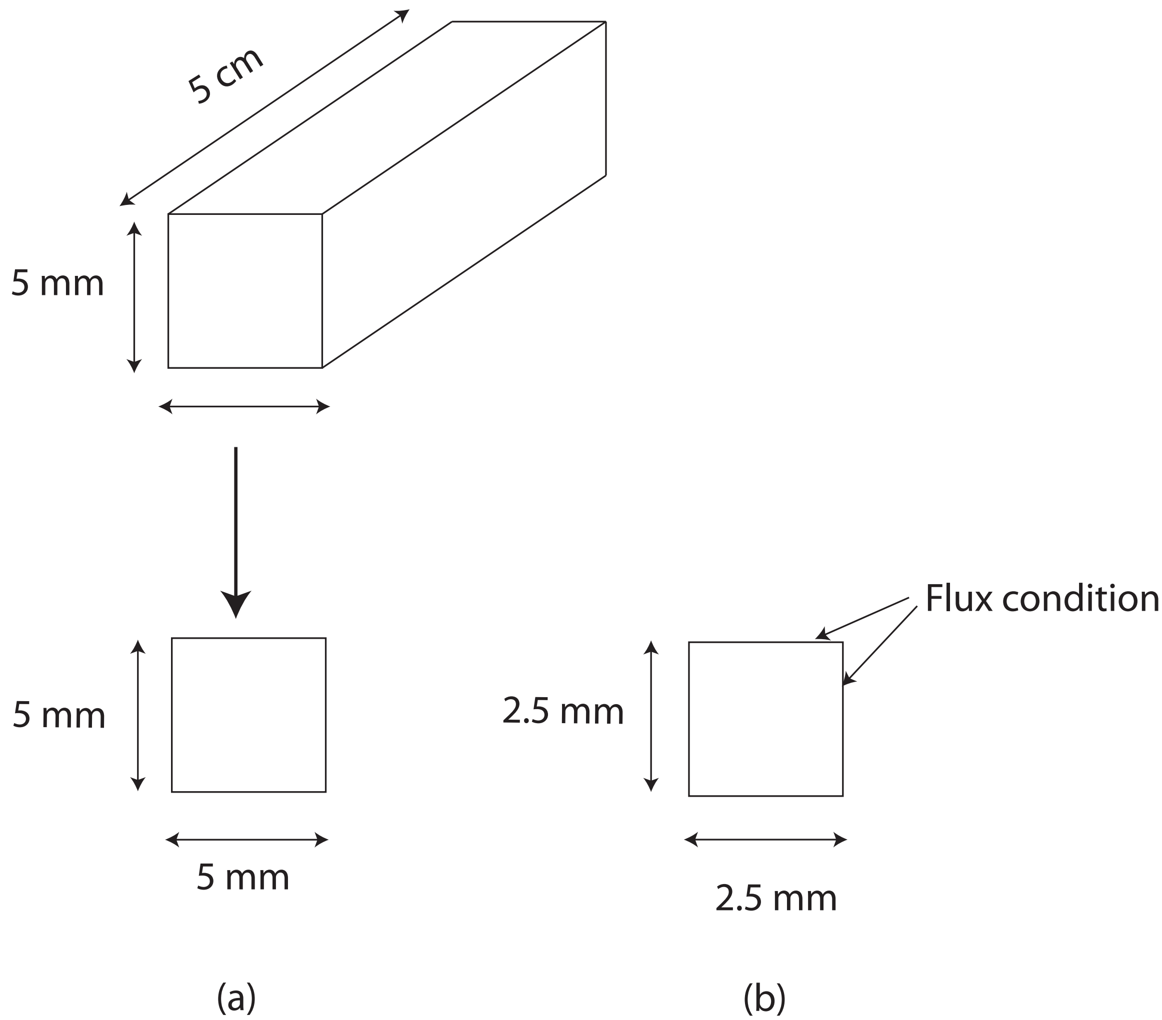


Figure 2.1: Schematic of the potato strip and the geometry used in COMSOL

2.3.2 Process Model

Modeling for food processes using the multiphase porous media approach has been reviewed elsewhere (Datta, 2007). In this section, only the governing equations relevant to the processes under consideration are briefly summarized and the reader should refer to Datta (2007) for details.

Assumptions

1) All phases are in continuum; 2) All phases are in local thermal equilibrium, which means temperature is shared by al the phases; 3) Shrinkage of the food material is ignored.

Governing Equations

The governing equations for non-isothermal transport of two-phases (liquid water and gas) in an unsaturated porous medium comprise of energy conservation and mass conservation of gas phase, c_g, water vapor, c_v, and liquid water phase, c_w, respectively:

$$\left(\rho_{eff} c_{p,eff}\right)\frac{\partial T}{\partial t} + \sum\left(\vec{n}_i.\nabla\left(c_{p,i}T\right)\right) = \nabla.\left(k_{eff}\nabla T\right) - \lambda\dot{I} + \dot{Q} \qquad (2.2)$$

$$\frac{\partial c_g}{\partial t} + \nabla.\left(\vec{n}_g\right) = \dot{I} \qquad (2.3)$$

$$\frac{\partial c_v}{\partial t} + \nabla.\left(\vec{n}_v\right) = \dot{I} \qquad (2.4)$$

$$\frac{\partial c_w}{\partial t} + \nabla.\left(\vec{n}_w\right) = -\dot{I} \qquad (2.5)$$

The energy equation is used to solve for temperature, T and the mass conservation equations for their respective concentrations. The gas concentration, c_g, is related to pressure by invoking the ideal gas law. The same set of governing equations is used for all three processes, the one difference being the heat source term, $\dot{Q}$ is non-zero only for the microwave heating process (more later). The volumetric heat source term, $\dot{Q}$, in microwave heating is given by Lambert's law (Ni et al., 1999):

$$Q = \frac{Q_{surf}}{\delta(x)} \exp\left(-\int \frac{dx}{\delta(x)}\right) \tag{2.6}$$

where Q_{surf} is the microwave flux at the surface and $\delta(x)$ is the penetration depth of microwaves at a distance x from the surface. The penetration depth is a function of moisture content.

The boundary conditions for multiphase porous media model are discussed in detailed in Halder et al. 2007 for the frying process. For the processes considered in the study, the boundary conditions for the two exposed surfaces (top surface and the right side surface in Figure 2.1) remain the same. Only the values of heat and mass transfer coefficients at the exposed boundary change are process dependent (as discussed in the Input Parameters section). The properties of the sample are averages of the phase properties by their mass or volume fractions (also discussed in Halder et al., 2007).

2.3.3 Input Parameters

The model of frying (Halder, 2007) is a multiphase porous media model which can be extended to processes like drying, baking and microwave heating with relatively minor changes, as basic physics behind all these processes is same. In order to model drying, there is a change in the heat transfer coefficient to 20 W/m^2K (Hanreich and Nicolics, 2001) and the mass transfer coefficient to

Table 2.1: Input parameters used in the simulations

Parameter	Drying	Baking	Microwave
Density (kg/m^3)			
water (ρ_w)	998	998	998
vapor (ρ_v)	Ideal gas	Ideal gas	Ideal gas
air ρ_a	Ideal gas	Ideal gas	Ideal gas
solid ρ_s	1528 [12]	1528 [12]	1528 [12]
Specific heat capacity (J/kg K)			
water c_{pw}	Eq. 45 [16]	4180 [36]	4180 [36]
vapor c_{pv}	Eq. 46 [16]		
air c_{pa}	1006 [8]		
solid c_{ps}	1650 [8]	1650 [8]	1650 [8]
Thermal conductivity (W/m K)			
water k_w	Eq. 47 [16]	0.65 [36]	0.65 [36]
vapor k_v	0.026 [8]		
air k_a	0.026 [8]	0.026 [8]	0.026 [8]
solid k_s	0.21 [8]	0.21 [8]	0.21 [8]
Intrinsic permeability (m^2)			
water $k^p_{in,w}$	5×10^{-14} [36]	5×10^{-14} [36]	5×10^{-14} [36]
air and vapor $k^p_{in,g}$	10×10^{-14}	10×10^{-14}	10×10^{-14}

Table 2.1 (Continued)

Parameter	Drying	Baking	Microwave
Viscosity (Pa s)			
water μ_w	5.468×10^{-4}	5.468×10^{-4}	5.468×10^{-4}
air and vapor μ_g	1.8×10^{-5}	1.8×10^{-5}	1.8×10^{-5}
Heat transfer coefficient (W/m^2K) h	20 [18]	15 [36]	15 [36]
Mass transfer coefficient (m/s) h_m	.01 [17]	0.007 [36]	0.007 [36]
Latent heat of vaporisation (J/kg) λ	2.26×10^6	2.26×10^6	2.26×10^6
Porosity ϕ	0.88 [36]	0.88 [36]	0.88 [36]
Vapor diffusivity in air (m^2/s) $D_{eff,g}$	2.6×10^{-6}	2.6×10^{-6}	2.6×10^{-6}
Ambient pressure (Pa) P_{amb}	101325	101325	101325
Microwave surface flux (W/m^2) F_0			30000

0.01 m/s (Halder, 2010). The input parameters for drying are given in detail in Table 2.1. The heat and mass transfer coefficients for the other two processes, microwave heating and baking are also given in Table 2.1.

2.3.4 Model Implementation

The governing equations for a process model are first solved to obtain time-dependent temperature and moisture spatial profiles for the duration of the process. A commercially available finite element software, COMSOL Multiphysics 3.5a (Comsol Inc, Burlington, MA), was used to solve the equations. The plane-stress (small deformation) analysis is then performed using COMSOL to predict the effective Young's Modulus as a function of time (as described in detail in Chapter 1).

2.4 Materials and Methods

2.4.1 High temperature drying

To verify model predictions of temperature, moisture content and Young's modulus during drying, experimental data were obtained for all three.

Potato samples (variety: Russet Idaho bought from a local grocery store) were used to study the change in mechanical properties experimentally. The potatoes were free of visible flaws. Thin samples (size $5 \times 5 \times 50$ mm) of potato were cut from the potato tuber. The average moisture content of a potato sample was found to be around 4.0 db.

Drying was then carried out at temperatures of 120°C, 130°C and 140°C in a hot air oven (VWR International oven, Model 1415M, Sheldon Manufacturing Inc., Cornelius, OR) for a period of 60 min each. Ten readings for Young's modulus at several time steps were taken for each temperature. The higher temperatures ensured that the potato samples reached their gelatinization temperatures and a significant temperature effect was captured.

According to the ASAE recommendation, the moisture content was found by drying the potato samples for 24 hours at 72°C (Mazza, 1982). In our study, it was found that the difference in mass at the end of the high-temperature drying process and after drying for 24 hours at 72°C was less than 0.001g. This is attributed to the small size (5mm thickness) of the sample and the high drying temperature.

All samples that had been once used for measurement of either moisture or Young's modulus were discarded. This work was replicated three times to enhance confidence and check variability. This experiment indicated the dependence of Young's modulus on moisture content at constant temperature.

2.4.2 Mechanical property measurement

Experiments were performed to capture Young's modulus of the material during the drying process. Young's modulus of the sample was measured using compression tests in a Q800-0666-DMA Q800 Analyzer during the processes of constant temperature drying, heating in water, and frying . The strain rate of the probe was 1.0%, which is within the elastic range in the case of the potato samples (Skinner, 1983). Young's modulus was determined using the compression test at each stage of drying (at several levels of moisture). This was done by applying a constant strain on the material for 30 seconds and measuring the corresponding stress generated, from which Young's modulus was obtained.

2.5 Results and Discussion

Temperature, moisture, and texture (Young's modulus) development during drying are predicted and compared with experimental results. The effects of drying temperature and sample size on development of Young's modulus are predicted. Finally, the framework for texture prediction is extended to baking, microwave heating, and frying, and comparative development of Young's modulus in the four processes is discussed.

2.5.1 Temperature, Moisture and texture (Young's modulus) development with time for drying

The moisture and temperature dependence of Young's modulus, shown in Fig. 2.2 and Table 2.2 respectively, are used to compute effective Young's modulus. Figs. 2.3, 2.4, and 2.5 show, respectively, variation of core temperature, average moisture content, and effective Young's modulus with time for the process of drying. Moisture loss is faster at higher drying air temperatures. Thus, as shown in Fig. 2.6a, Young's modulus increases faster with time for higher drying air temperatures. The same final value for Young's modulus is predicted for all drying air temperatures since the final moisture content is the same. Fig. 2.6b also shows the time needed for each drying temperature to reach the same final value of Young's modulus. For the range of parameters considered here, there is a linear decrease in time needed to reach the same value of Young's modulus as temperature increases.

Table 2.2: Temperature dependence of Young's modulus, in terms of first-order reaction rate constant, k_f, and activation energy, E_a, at two temperatures (Thussu and Datta, 2010)

85°C		95°C	
k_f (/min.)	E_a (kJ/mol)	k_f (/min.)	E_a (kJ/mol)
0.372	53.95	0.1165	65.95
0.5595	92.83	0.1494	40.34
0.6579	70.93	0.4712	86.78

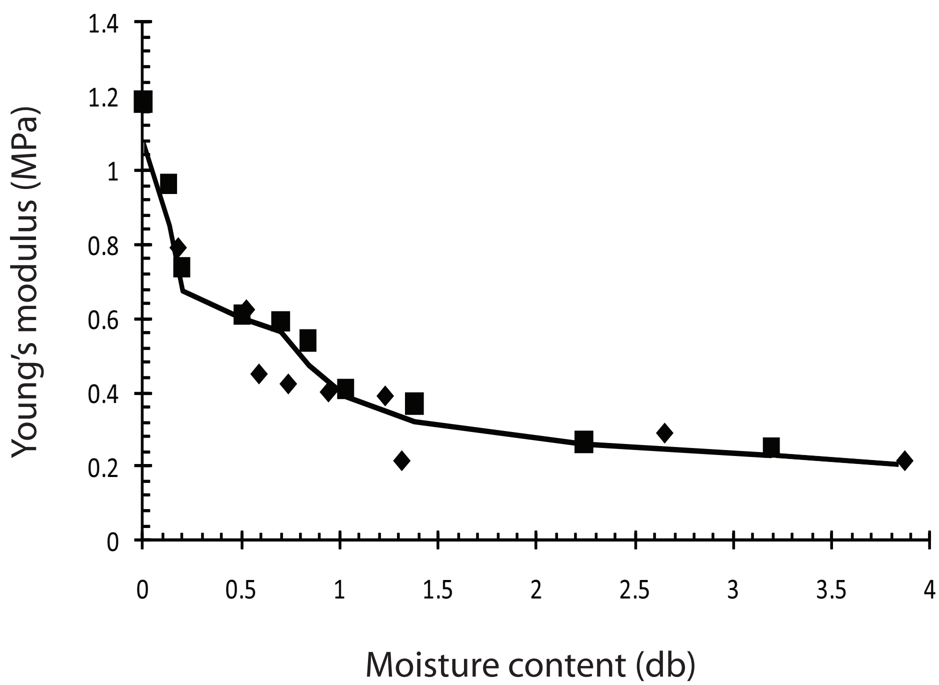


Figure 2.2: Moisture dependence of Young's modulus (Thussu and Datta, 2010). The points are measurements and the solid line shows the data used as input parameters in mechanical analysis

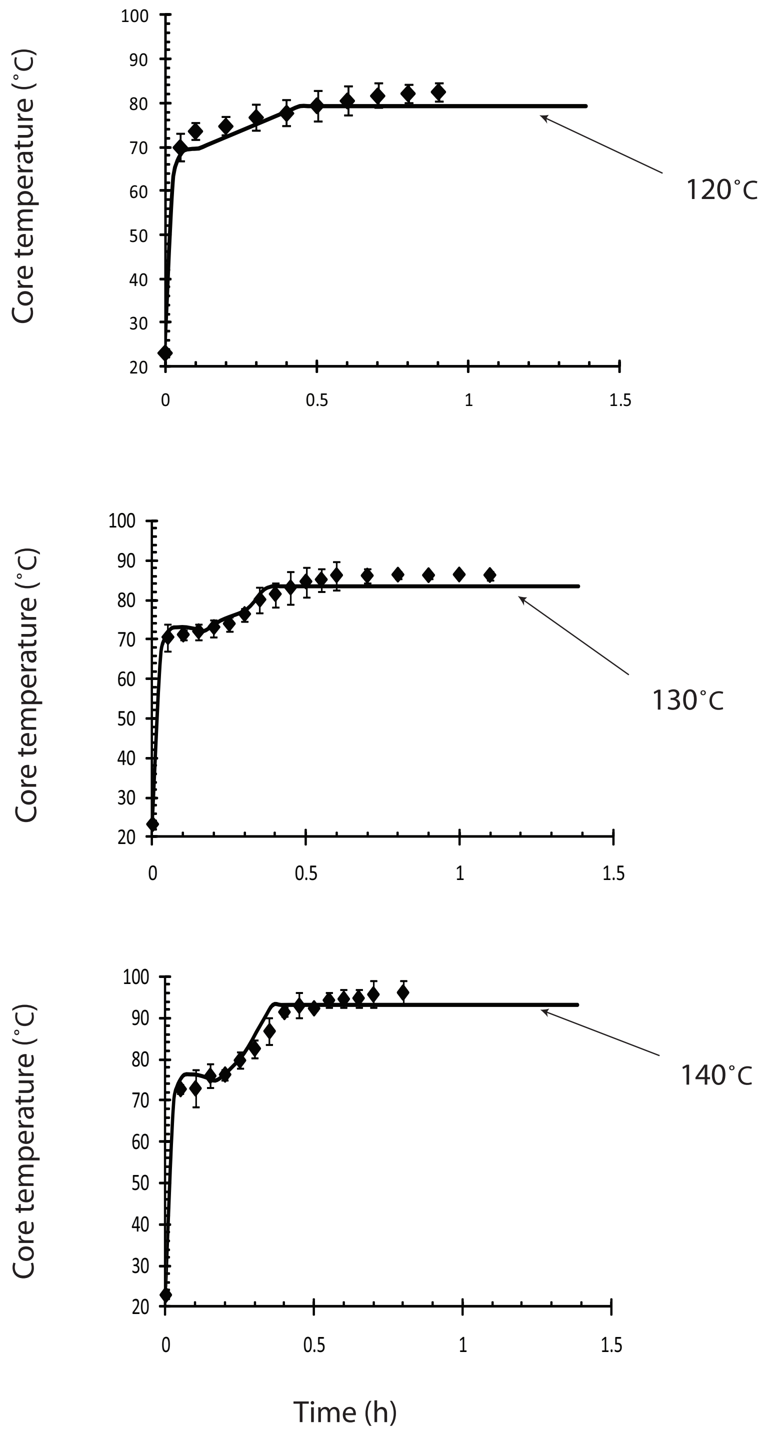


Figure 2.3: Variation of temperature at the core with time during drying

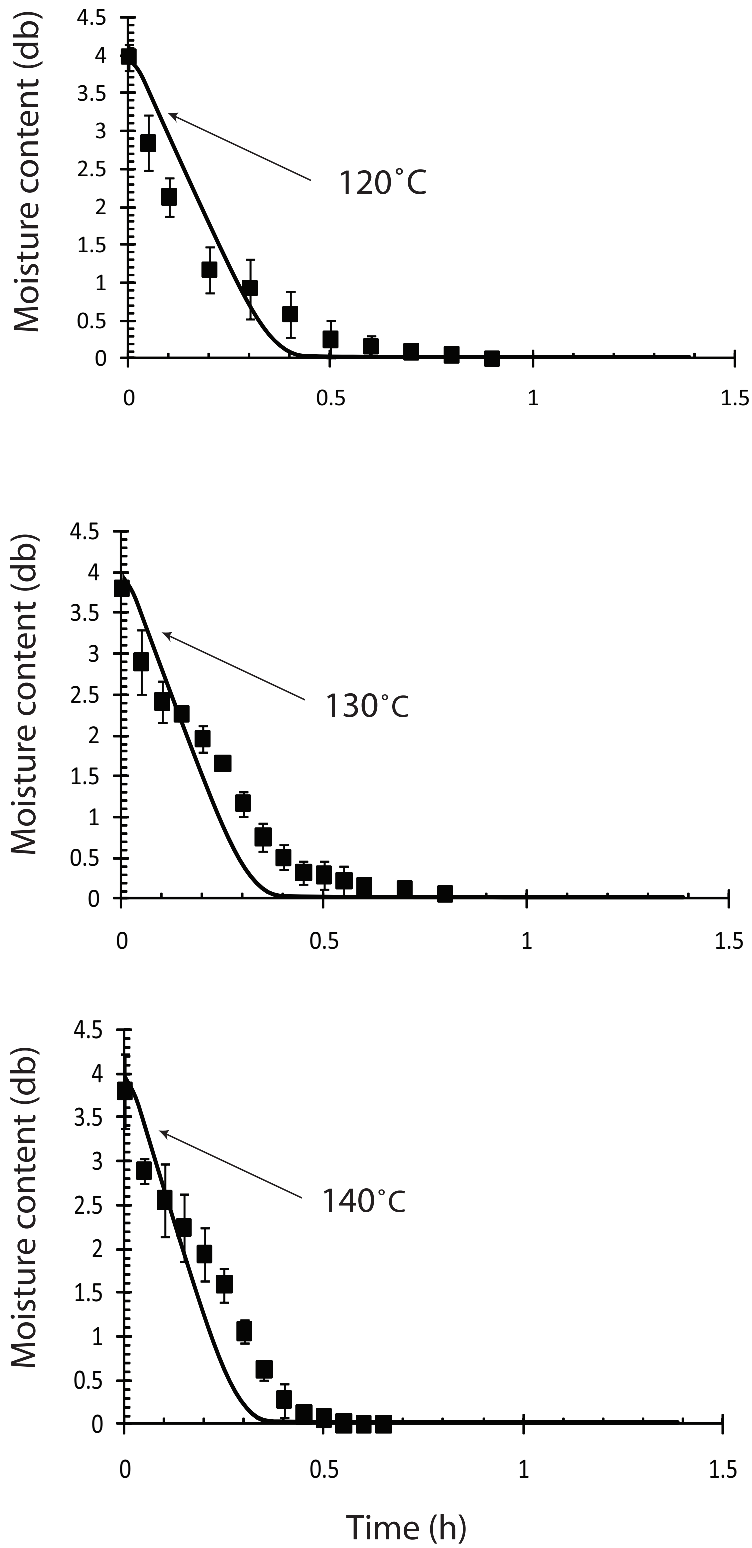


Figure 2.4: Variation of average moisture content with time during drying

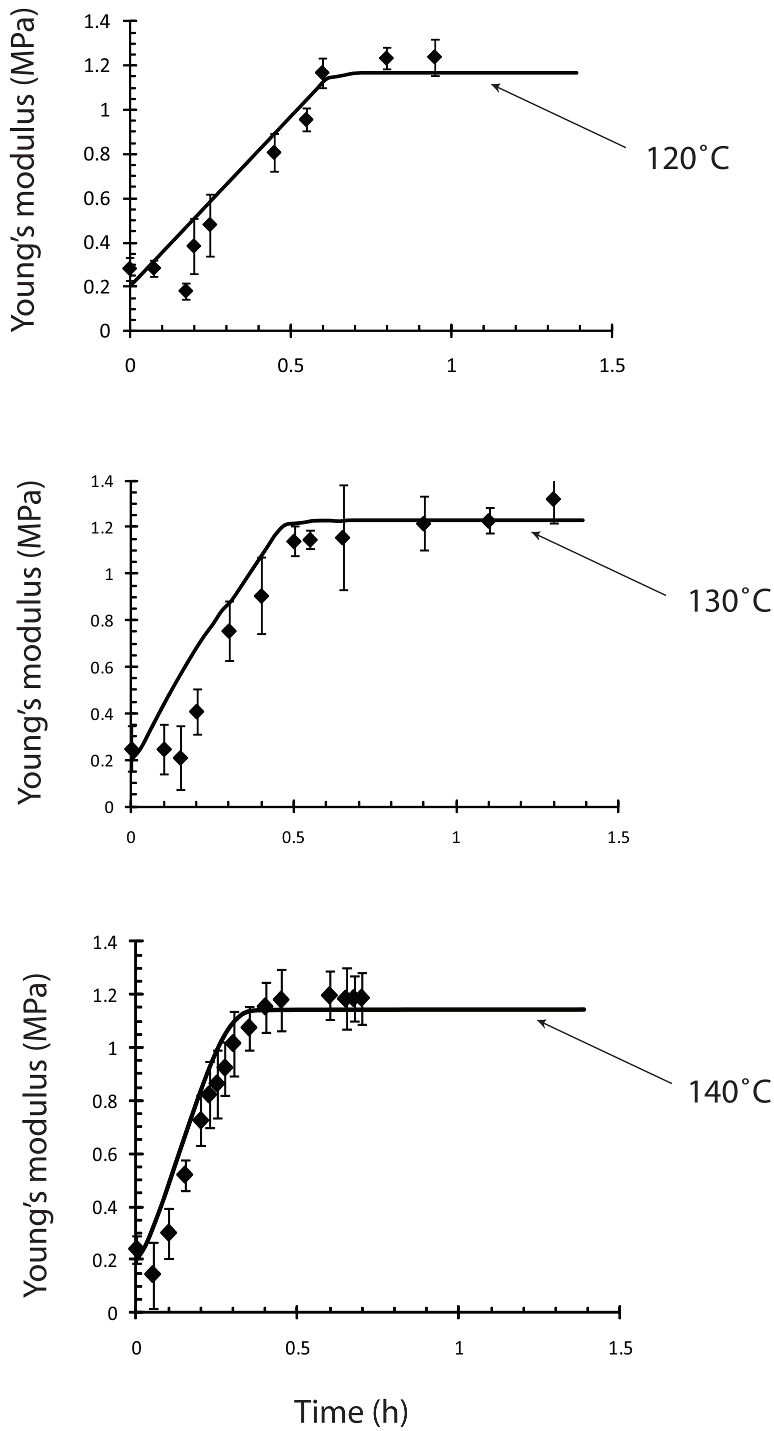
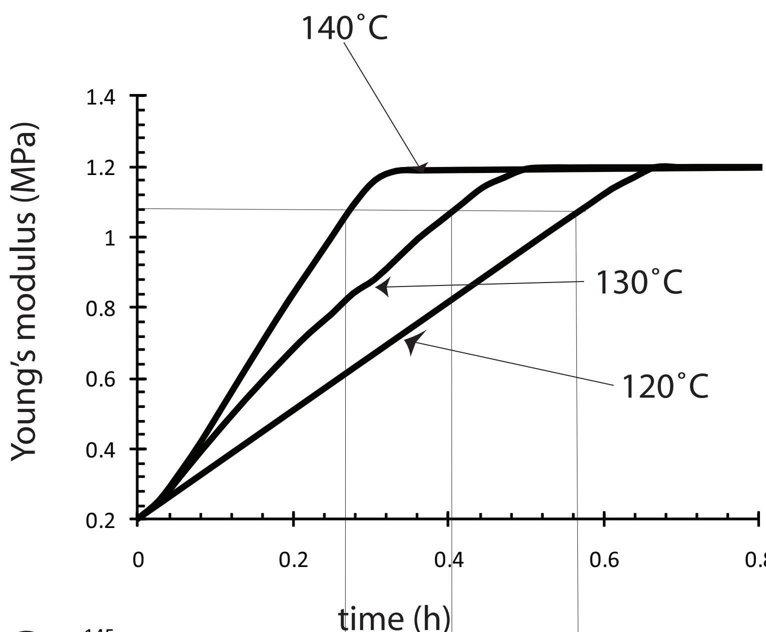


Figure 2.5: Variation of Young's modulus with time during drying

(a)



(b)

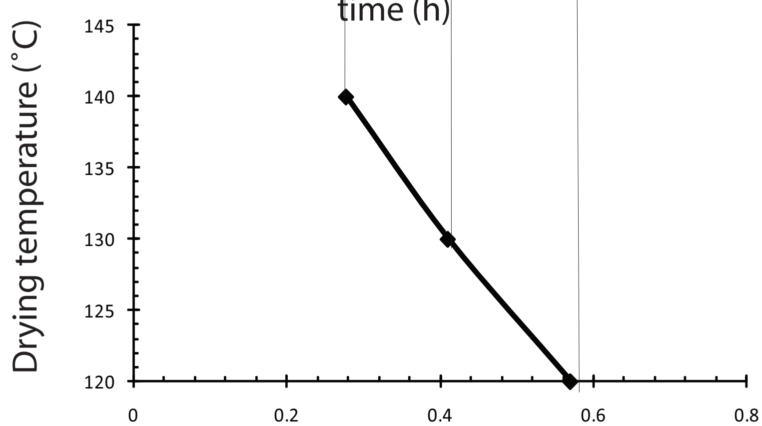


Figure 2.6: (a) Change in Young's modulus with drying temperature; (b) time taken by the sample to reach the desired textural level

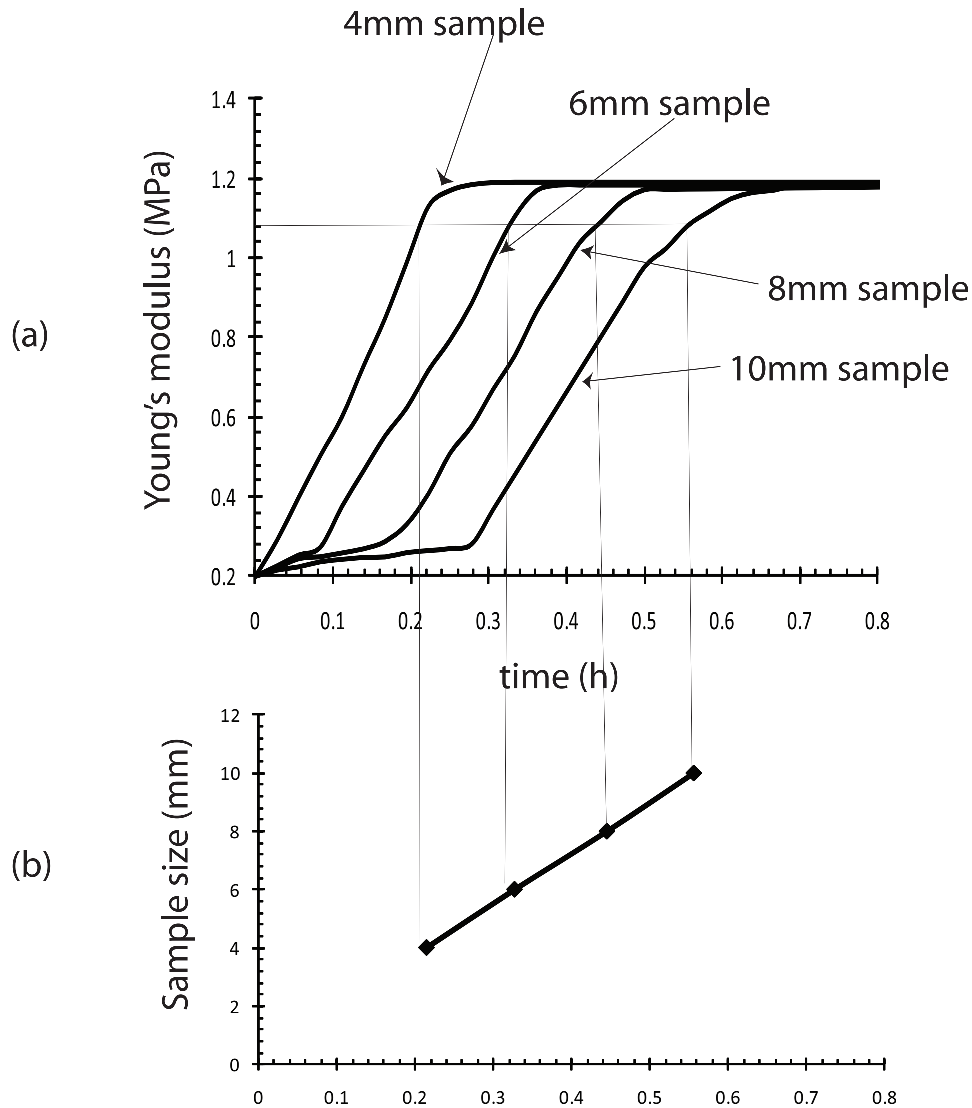


Figure 2.7: (a) Change in Young's modulus with sample size; (b) time taken by the sample to reach the desired textural level

2.5.2 Texture development during drying: Effect of sample size

Fig. 2.7a shows how Young's modulus changes with time for variations in sample size. As the sample size increases, the fraction of its moisture lost per unit time decreases. Volume increases much faster with greater sample size than with greater surface area through which moisture loss occurs. For a larger sample, the crust that forms due to moisture loss at the surface is thinner compared with the size of the sample. This leads to reduced effective modulus of the sample (since the inside is always soft, with a lower modulus value) for a larger size for the same duration of heating. In other words, modulus development lags in the larger sample, as expected qualitatively. Fig. 2.7b shows another way to capture the size effect on modulus development. Here, time to reach the same final modulus value is plotted for various sizes. Again, for the range of parameters considered here, time taken by various sample sizes to reach the same final value of Young's modulus increases linearly with size.

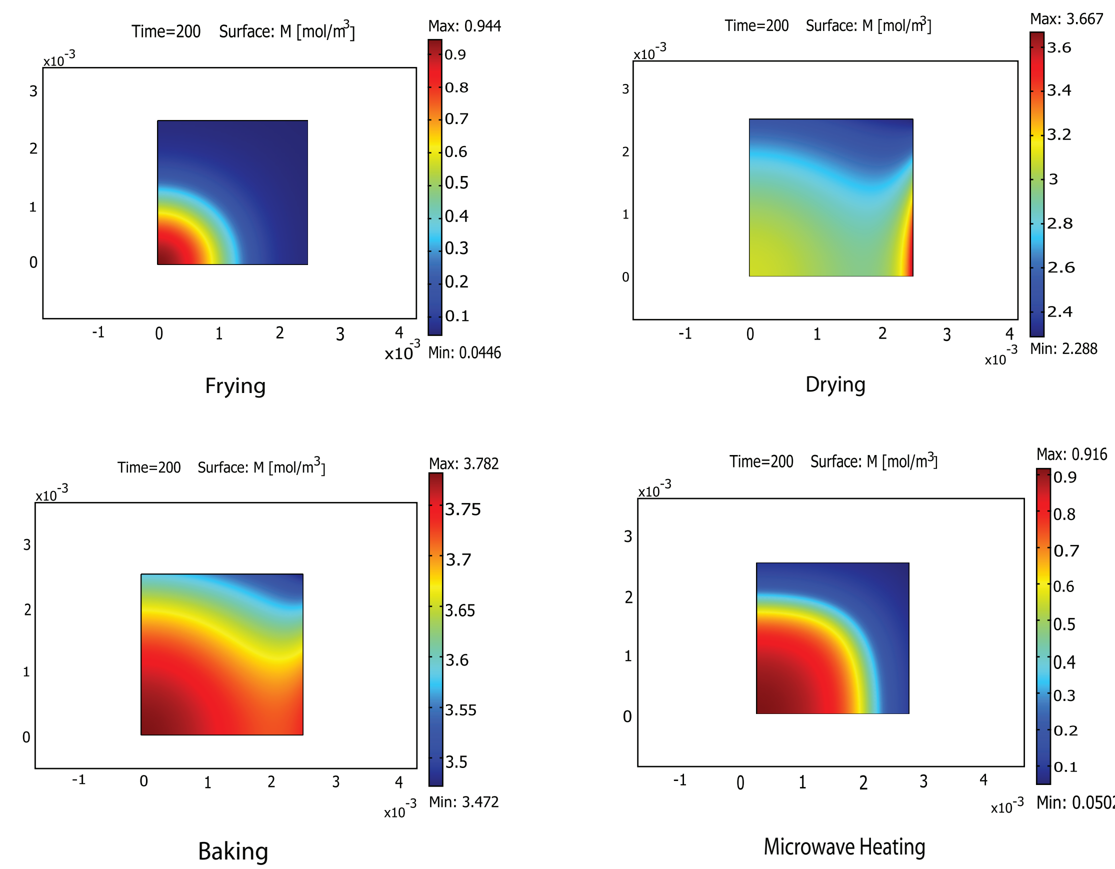


Figure 2.8: Comparing change in moisture content by process

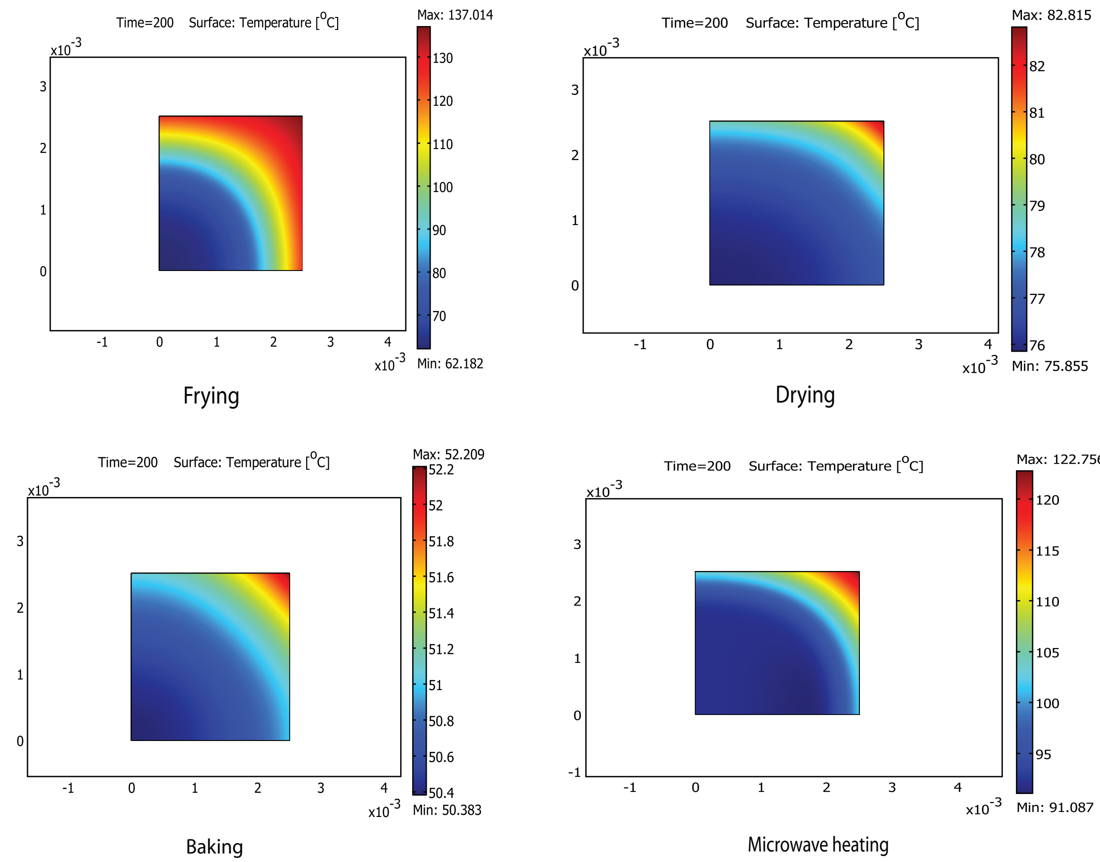


Figure 2.9: Comparing change in temperature by process

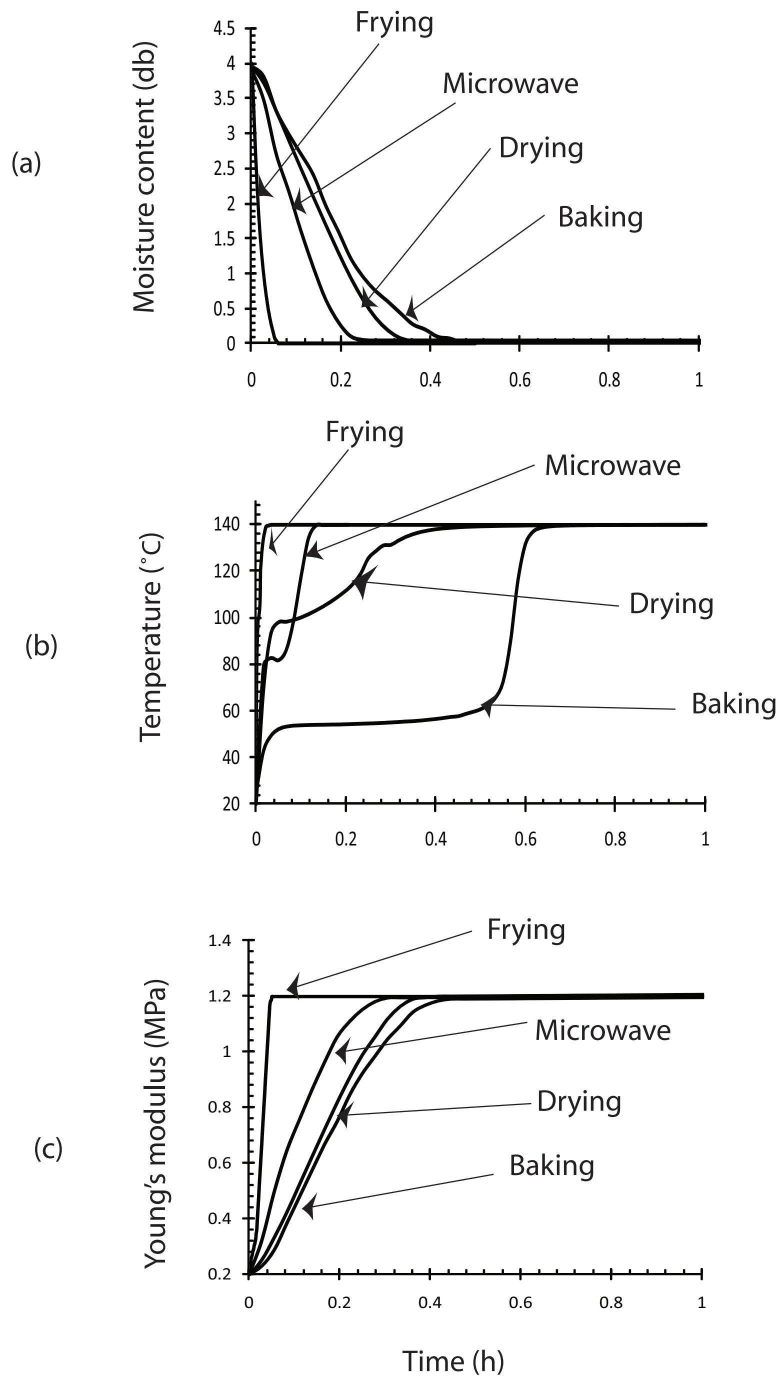


Figure 2.10: Comparing (a) change in moisture content, (b) change in temperature by process and (c) Young's modulus

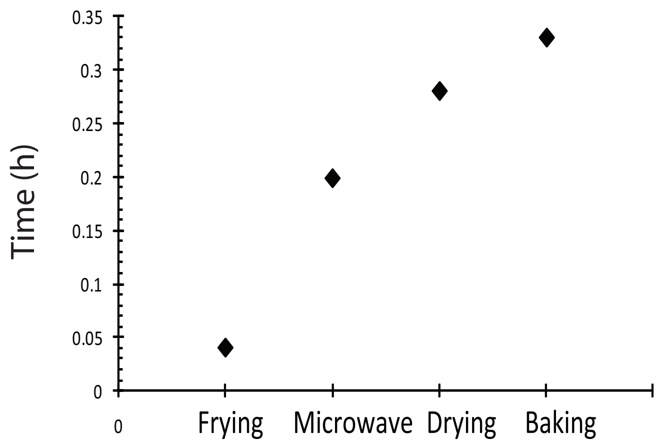


Figure 2.11: Change of process with time

2.5.3 Comparative texture development in four processes

The framework for texture (Young's modulus) prediction, developed and verified in the previous sections for drying, would be more useful if it could be extended to prediction of texture in other processes. Note that the framework has already been used successfully for frying (Thussu and Datta, 2010). To demonstrate the more general applicability of the framework, it is extended to two other processes, baking and microwave heating. Process models for baking and microwave heating have been discussed under Problem Formulation. Fig. 2.10 compares average temperature, average moisture, and effective Young's modulus development over time for all four processes side by side. Since the temperature and moisture histories for each of the processes differ, the transient texture development of the processes are also different. The process with the fastest moisture loss (frying) produces the fastest texture development. It is also instructive to compare the spatial variation of temperature and moisture at a given time, for all four processes, which is shown in Figs. 2.8 and 2.9. As can be seen in these figures, for a duration of 200 s of each of these processes, frying achieves the lowest moisture, the highest temperature, and the desired level of texture. As baking and drying are slower processes, there is still a significant amount of moisture left. Figure 2.11 shows the time to reach a final texture level, for each of the four processes. As expected, since frying produces the fastest moisture loss, it takes the least time to develop the desired texture, followed by microwave heating, drying, and baking.

2.6 Conclusions

Change in effective Young's modulus during drying of a potato sample was predicted starting from a physics-based model of the process and experimentally observed temperature and moisture dependence on local modulus. Change in the moisture content of the material had the most dominant effect on Young's modulus. Thus, at higher temperatures, where the moisture loss was faster, predicted Young's modulus showed the fastest increase. In a larger sample, modulus development is slower since the fraction of moisture lost per unit time decreases. For a given final modulus value, the required (drying) time increases linearly with any decrease in drying air temperature and increase in sample size. The physics-based prediction of Young's modulus (measure of texture), proven here for drying and in past work for frying (Thussu and Datta, 2010) is extended to baking and microwave heating. Comparative modulus development in four processes-baking, drying, microwave heating and frying-is observed to follow that order, i.e., frying produces the fastest increase in modulus and baking the slowest. This order follows the order of moisture loss, since frying has the fastest moisture loss and baking the slowest. The framework of texture (Young's modulus) prediction thus developed and applied to four processes is considered generally applicable to other moisture removal processes and therefore can be used to predict texture for a wide variety and combination of processes.

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